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PROJECT SHERWOOD

An account of the program
in controlled thermonuclear reactions
carried out by the
United States Atomic Energy Commission
during the period 1951-1958

PROJECT SHERWOOD

The U. S. Program in Controlled Fusion

by

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U.S.A.E.C.

PREPARED FOR THE
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PREFACE

This book is a brief account of the development of the United States program in controlled thermonuclear reactions (Project Sherwood) from its inception in 1951 to the early part of 1958. Prepared at the request of the U. S. Atomic Energy Commission's Division of Information Services, the book is written mainly for those who have little or no familiarity with the subject, but who would like to become acquainted with this new and important field. Specifically, its purpose is to give the reader some insight into the origin of the program, the basic problems involved, the approaches being pursued in the United States, the difficulties encountered, the present status of the effort, and the outlook for eventual success.

Effort has been made to present the material so that it can be followed by those with relatively little technical background. The few equations which appear have been relegated to footnotes and may be skipped at first reading with little loss of understanding. For those who wish to refresh their memories, an appendix provides a brief discussion of some of the basic principles of physics and nuclear structure essential for following the text. In addition, definitions of new or unusual terms are given in a glossary.

The presentation is generally chronological. The first two chapters deal with fundamental matters common to all approaches being pursued. Chapters 3 through 8 present the basic principles of the major Sherwood projects and discuss the work carried out to the end of 1954.

Chapter 9 is devoted to the important topic of stability, which came to a head late in 1954. Developments in the program from 1955 to early 1958 are then covered in Chapters 10 through 18. Finally, the last chapter reviews the present status of the effort and peers just a bit into the future. The charts in Appendix X tabulate the features and characteristics of important experimental models which have been built.

This short book attempts only to summarize, in "broad-brush" fashion, the more important developments of the controlled fusion program, with particular emphasis on the experimental work. To avoid undue complexity in the presentation, it has been necessary, regrettably, to omit discussion of many side projects and supporting activities. Needless to say, those engaged in these efforts have contributed substantially to the progress of the over-all program.

I would like to express here the great pleasure derived from my period of close association with the Sherwood project and those engaged in it. I am particularly indebted to W. R. Baker, N. C. Christofilos, S. A. Colgate, W. Faust, H. Grad, T. H. Johnson, P. W. McDaniel, R. F. Post, A. E. Ruark, E. D. Shipley, L. Spitzer, Jr., E. Teller, J. L. Tuck, and C. M. Van Atta, not only for their cordial cooperation during that period, but also for their helpful comments on sections of this text relating to work under their supervision. They and those working with them can take great pride in participating in what, in my mind, is one of the most fascinating and challenging programs ever undertaken.

The program also owes a debt of gratitude to AEC Chairman Lewis L. Strauss for his strong and continuing interest in and support of the Sherwood effort during its entire history.

Sincere thanks are due John A. Hall, Director of the Commission's Division of International Affairs, for allowing me to set aside other duties temporarily in order to write this book. Appreciation is also expressed to members of the Commission's Industrial Information Branch, Technical Information Service, for their assistance in the preparation of this book—particularly to Sidney F. Lanier, book project officer, and J. William Young, technical book program supervisor. I am grateful to Joseph S. Banks, the publisher's Art Director, for his work on the book's illustrations.

Lastly, I dedicate this book to my wife, Barbara M. Bishop, for her patience and understanding.

It is hoped that, thanks to cooperation from many people, this account is substantially accurate. I assume full responsibility for such errors as may occur.

Paris, France
June 1958

AMASA S. BISHOP

INTRODUCTION

It is not too much to say that man is presently engaged in one of the most important and challenging programs of scientific research and development that has ever been undertaken.

From the beginning of history, energy has played an important role in the development of civilization. Starting with fire, the harnessing of each new and improved source of energy has resulted in significant advances in technology and has opened new vistas toward the future. The industrial revolution of the last century, for example, was founded in large part on harnessing the fossil fuels, coal and oil, for useful purposes. Subsequent developments continuously and rapidly expanded their use to provide heat, power, and propulsion.

Ever-increasing energy requirements have spurred world-wide exploration for these fuels. In spite of extensive exploration, however, the practical resources of conventional fuels are dwindling at an alarming rate, especially in the older industrial areas. Nuclear power from the fission of heavy elements will help to meet the needs of this energy-hungry world for a time, and intensive effort is being devoted to the practical application of fission energy. However, the world reserves of even the fissionable fuels appear to have their limits.

It is therefore highly significant, and indeed fortunate, that a vast new source of energy looms on the horizon—the energy of nuclear *fusion.* While the problems associated with the controlled release of fusion energy are staggering in magnitude, the rewards to be gained are of comparable size. If present efforts are successful, man will have found the ultimate solution to one of his most pressing problems. He will have developed a new and practical source of energy which will meet his needs, not for just the next hundreds or thousands of years, but for as far into the future as he can see.

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CHAPTER 1

BASIC PRINCIPLES OF CONTROLLED FUSION

It has been known for many years that energy may be released by modifying the structure of certain atomic nuclei.* In one method— the well-known process of nuclear fission—release of energy results from the splitting of heavy nuclei into lighter fragments. An alternative and potentially much more important method is the combination of certain very light nuclei into heavier components. This method is called the process of fusion.

As background for the discussions later in the book, this chapter will be devoted first to comparing briefly the processes of fission and fusion, then to considering the potential advantages associated with the latter process, and finally to discussing the basic requirements for achieving the controlled release of fusion energy.

THE PROCESS OF FISSION

The key ingredients of the fission process are the nuclei of certain very heavy elements at the upper end of the periodic table, such as uranium-235 and plutonium. A neutron, because it has no charge, can easily penetrate into any such nucleus. Its presence can cause the nucleus to become highly unstable and to undergo fission—that is, to split into two smaller fragments of roughly comparable size (see Fig. 1–1). In the process, several additional neutrons are re-

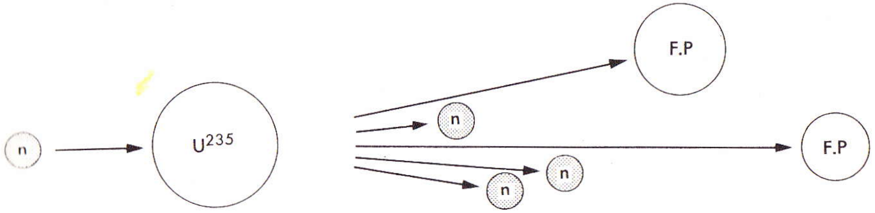

FIG. 1–1. THE FISSION PROCESS. The entry of a neutron (n) into a U^{235} nucleus causes the latter to split into two fission products (F.P.) of roughly equal size. Several neutrons are emitted in the process.

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* A brief and elementary review of several topics in atomic and nuclear structure is given in Appendix I.

leased which, in turn, can cause other nuclei to undergo fission. If care is taken to minimize the loss of neutrons in nonproductive processes, it is possible to perpetuate a chain reaction.

In each fission process, some 200 million electron volts (200 Mev) of energy is released as a result of the conversion of mass into energy. The total mass of the product nuclei is less than that of the original nuclei, and the difference in mass is converted to energy.*

The released energy appears principally as energy of motion of the fission fragments and produces heat in the surrounding materials. In the case of a self-sustaining chain reaction (as in a nuclear reactor), large amounts of heat may be produced. By passage of a suitable coolant through the reactor, the heat produced can be continuously removed and used to generate electric power.

The Process of Fusion

In the fusion process, on the other hand, the basic principles are in many respects just the opposite of fission. Here the key ingredients are the nuclei of certain very light elements, i.e., elements at the low end of the periodic table. The combination (or fusion) of such particles to form heavier and more tightly bound nuclei can result in the release of significant amounts of nuclear energy. Fusion reactions of this type are, in fact, responsible for the enormous energy generated in the sun and other stars. (A brief description of stellar processes is given in Appendix III.)

It is important to recognize that, in the fusion process, each of the interacting nuclei is positively charged. As a result, they strongly repel one another.† In order for two nuclei to coalesce, they must be made to collide with high enough relative velocity to overcome the barrier of electrostatic repulsion which tends to keep them apart. As would be expected, the magnitude of the barrier increases with increase of charge on the interacting nuclei. To keep the barrier as low as possible in fusion experiments, it is desirable to select a fuel with low nuclear charge.

The element with the lowest atomic number is hydrogen, with its two other iostopes, deuterium and tritium (see Appendix I). Of these isotopes, hydrogen is by far the most abundant; deuterium occurs in nature with an abundance of about one part in six thousand of hydrogen; tritium, however, is a radioactive isotope which is virtually nonexistent in nature and must be manufactured. Hydrogen itself, while constituting the fuel in stellar processes, is not suitable for practical fusion reactions on Earth; it undergoes fusion at a much slower rate than would deuterium or tritium under the same conditions. These latter isotopes, however, are of great interest as fusion fuels. A reaction of primary importance is

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He}^4 + \mathrm{n} + 17.6\ \mathrm{Mev}.$$

Here a deuterium nucleus (designated by the symbol D and consisting of a proton and one neutron) undergoes fusion with a tritium nucleus (designated by T, and consisting of a proton and two neutrons). In this reaction, a helium-4 nucleus and a neutron are produced, and 17.6 Mev of energy is released (Fig. 1–2).

A reaction of even greater interest (since it involves deuterium alone as fuel) is the fusion of two deuterons. Here there are two reactions which may occur with roughly equal probability:

$$\mathrm{D} + \mathrm{D} \begin{array}{l} \nearrow \mathrm{He}^3 + \mathrm{n} + 3.2\ \mathrm{Mev} \\ \searrow \mathrm{T} + \mathrm{p} + 4.0\ \mathrm{Mev} \end{array}$$

It is seen that, in each of the above fusion reactions, energy is released. As was the case for the fission process, the released energy results from a transformation of mass into energy: the total mass of the product nuclei (on the right side of the arrows) is less than the mass of the interacting nuclei (on the left side), and the difference in mass has been converted to energy. While the energy released in the above fusion reactions is appreciably less than that released

---

* The relationship between mass M and energy E is given by Einstein's well-known formula, $E = Mc^2$, where c is the velocity of light. If the mass is given in grams and c in cm/sec, then the energy is expressed in ergs. [One electron volt (ev) $= 1.60 \times 10^{-12}$ erg.]

† The force of repulsion F between two nuclei possessing charges of Z_1e and Z_2e is given by

$$F = \frac{Z_1Z_2e^2}{r^2},$$

where e is the electronic charge, Z_1 and Z_2 are the atomic numbers of the nuclei, and r is the distance between them.

in a fission reaction, the energy yield *per unit mass* of fuel (per gram, say) is slightly greater from fusion than from fission.

It may be shown that the initial energy required by the interacting particles to overcome the barrier of electrostatic repulsion is only 0.1 Mev or less. Since the energy released in the above reactions lies between 3 and 18 Mev, the net energy gain in any one fusion process is appreciable. This gain appears in the form of kinetic energy of the reaction products, the lion's share going to the lighter of the two nuclei. If the number of fusion reactions can be made sufficiently large, useful amounts of net energy will be released and may be harnessed for practical purposes.

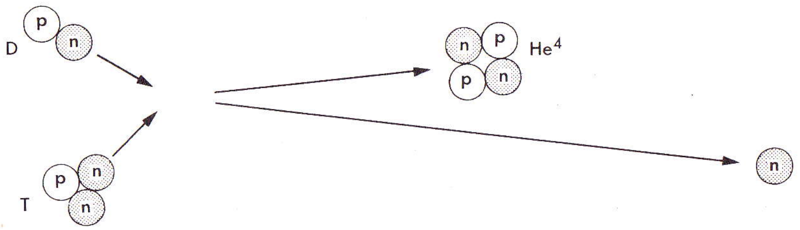
ADVANCES ASSOCIATED WITH CONTROLLED FUSION POWER

The ultimate goal of the Sherwood program, of course, is the production of economic power from the controlled release of fusion energy. While, as we shall see, the problems to be solved are of enormous difficulty, it is clear that success in this field would constitute an achievement of the greatest significance. The following are several of the more important advances which may be anticipated if controlled fusion should prove feasible.

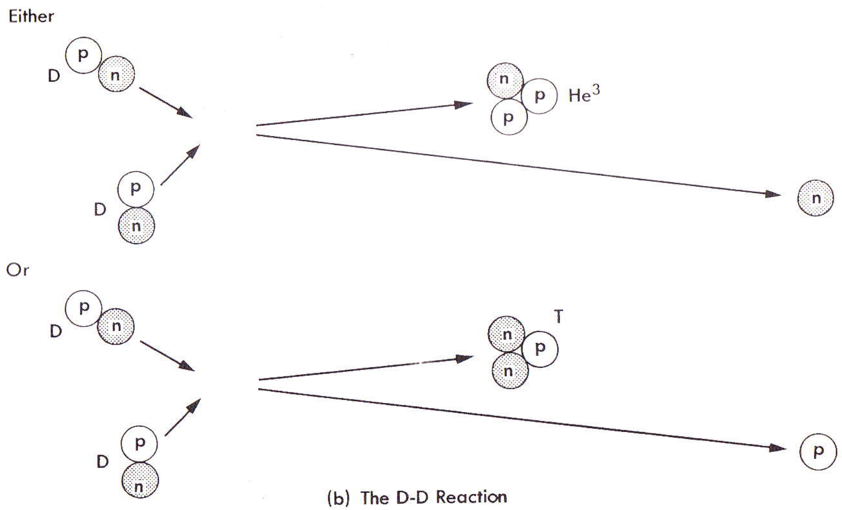
Unlimited energy source

Of primary interest is the fact that if man can learn how to achieve the fusion of deuterium under controlled conditions, an energy source virtually without limit will be within his grasp. As already mentioned, deuterium occurs naturally in nature, with an abundance of about one part in six thousand of hydrogen. The total amount of deuterium in the oceans is estimated to be about 10^{17} pounds. It may readily be shown that the energy content of this fuel has a value of some 10^{20} kilowatt-years. Thus at the current rate of energy consumption (about 5×10^{9} kilowatts), there would be enough deuterium on the Earth to provide a source of energy for some twenty thousand million years!

Moreover, the cost of this fuel is negligible. Even with present means of extracting deuterium from water, its cost per unit of fuel value is but a tiny fraction of the cost of conventional fuels. To be more specific, the amount of deuterium in a gallon of water is about



(a) The D-T Reaction



(b) The D-D Reaction

FIG. 1–2. THE FUSION PROCESS. Part (a) shows the reaction between deuterium and tritium nuclei; part (b) illustrates the two possible reactions which may occur between deuterium nuclei alone.

$\frac{1}{8}$ of a gram, and the cost of its extraction would be less than 4 cents. However, its energy content, if it were burned as a fuel in a fusion reactor, would be the equivalent of some 300 gallons of gasoline.

Inherent safety

A second important feature is that a controlled fusion device is expected to be inherently safe. Since only very small amounts of fuel would be within the reactor at any instant of time, there would be no possibility of an explosion or a "runaway" reaction.

Nonradioactive reaction products

A third consideration is that, in contrast to the case of fission, a fusion reactor would present no problem of disposal of radioactive fission products. The products of fusion, if the nuclear burning were carried to its proper completion, would consist of nonradioactive nuclei only. (This is not to say, however, that the controlled fusion reactor itself would be free from radioactivity. The intense flux of neutrons produced in the fusion process would cause the surrounding structural materials to become highly radioactive, and adequate shielding would be required.)

Direct generation of electricity

An additional point of potentially great significance is the fact that, in principle at least, a controlled fusion device offers the possibility of *direct* generation of electric power. Such an achievement could eliminate the costly and inefficient stage of a heat cycle.

Basic Requirements for Achieving Controlled Fusion

Before this tantalizing source of energy can be tapped, however, there are many formidable difficulties to be overcome. To grasp the magnitude of these difficulties, it is desirable to discuss below some of the basic requirements in achieving the controlled release of fusion energy.

High temperatures

In contrast with the fission process, exceedingly high temperatures (hundreds of millions of degrees) are required for fusion reactions.

The necessity for these temperatures is the following. For fusion to occur, two nuclei must come sufficiently close to each other that short-range nuclear forces may interact, permitting the particles to coalesce. We have already seen that because of the positive charge on the nuclei they tend to repel each other strongly. To overcome this force of repulsion, they must be made to collide at rather high velocities. Even then, it is far more probable that the nuclei will rebound (scatter) elastically than that they will undergo fusion. The nuclei must therefore be confined somehow in a region where they can approach each other time and time again until fusion eventually takes place.

The above condition of having the particles in a confined region and moving at high kinetic energies randomly with respect to one another may be described by saying that the particles have a high temperature. The kinetic energies which the nuclei require to overcome the force of repulsion and begin to fuse together correspond to temperatures of 100 million degrees Kelvin or higher—temperatures even higher than those in the interior of the sun.*

Rather low density

At the extremely high temperatures required for fusion, all the fuel atoms are entirely stripped of their electrons. The result is a wholly ionized gas, or "plasma," consisting of charged nuclei and electrons in rapid random motion. This gas exerts an outward pressure against the "walls" which confine it. To keep the plasma pressure within reasonable bounds at such high temperatures, the density of the gas must be kept rather low—of the order of 10^{15} particles per cubic centimeter in most cases. A gas of this density, corresponding to approximately 1/10,000 the density of the atmosphere, is generally considered to be practically a vacuum.

It must be pointed out, however, that the density must not be *too* low; otherwise, as we shall see, the rate of energy generation per unit volume from fusion reactions will be too small to be of practical interest. In general, the density will fall in the range from 10^{14} to 10^{18} particles per cubic centimeter. (From here on in this book, if the density of a plasma falls in the lower end of this range, or below, it will be called a "low-density plasma"; if at the upper end, a "high-density plasma.")

---

* The relationship between energy and temperature is the following: 1 ev of energy corresponds to 1.16×10^4 degrees Kelvin. Thus 10 kev (kilo-electron volts) corresponds to roughly 100,000,000°K. (In the Kelvin, or absolute, scale of temperatures, the zero is approximately −273° Centigrade. Thus, at these high temperatures, there is almost negligible difference between the Kelvin and Centigrade scales.)

Self-sustaining process

A third requirement of any useful fusion device is that the reaction be self-sustaining. That is to say, once the plasma temperature has been increased to the point at which nuclear fusion occurs at an appreciable rate, the energy released in the plasma (not counting that carried off by neutrons) must be at least sufficient to maintain that temperature.

The rate of energy generation in a hot plasma may be computed rather easily.* Its value (P_g) is found to increase rapidly with increasing temperature of the plasma, as shown in Fig. 1–3.

Counterbalancing this rate of energy generation are various mechanisms of energy loss from the reaction region. Radiation from the plasma itself is one of the most important. Here it must be noted that the particle densities in fusion devices are far too low to permit radiation equilibrium. As a result, the dominant radiation process will be by ordinary "bremsstrahlung," i.e., the radiation resulting

---

* The essence of the matter is the following. Consider a fully ionized gas of identical nuclei (nothing but deuterons, for example). The probability per unit time that a deuterium nucleus will undergo a fusion reaction is simply equal to $n\sigma v$, where n is the density of plasma nuclei, v is the velocity of the nucleus under consideration, and σ is the "cross section" for a fusion reaction. (The variation of σ with particle energy is shown in Fig. 1–4 for several reactions of interest.) Taking into account now *all* the interacting nuclei, the total reaction rate is equal to $\frac{1}{2}n^2\overline{\sigma v}$, where the $\frac{1}{2}$ has been inserted to avoid counting the same interaction twice, and where the bar over the ($\overline{\sigma v}$) term takes into account the fact that the velocities of the particles are not all the same but will have, in general, a Maxwellian distribution corresponding to the temperature of the plasma. The total energy generated per cubic centimeter per second is then seen to be simply $P_g = \frac{1}{2}n^2\,\overline{\sigma v}E_0$, where E_0 is the energy released in each fusion reaction. For temperatures below one hundred million degrees Kelvin, the quantity $\overline{\sigma v}$ increases very rapidly with plasma temperature.

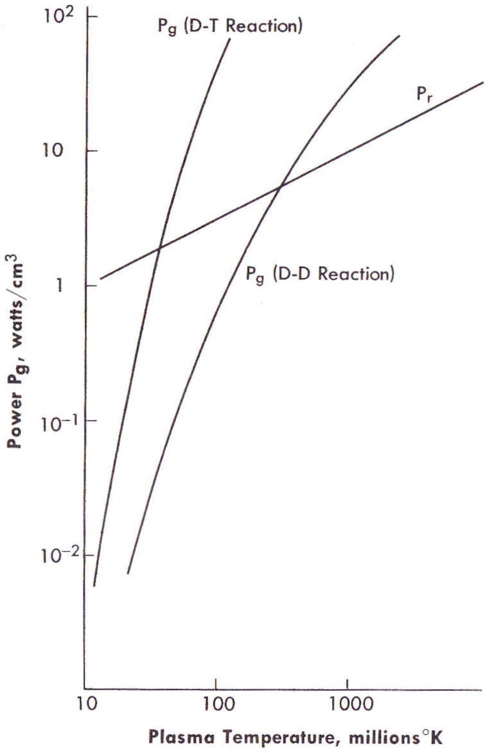


FIG. 1–3. POWER GENERATED VS. PLASMA TEMPERATURE. The graph shows the total power generated (P_g) per cubic centimeter for both the D-T and the D-D reactions as functions of temperature. Also shown is the power radiated (P_r). For a given reaction to be self-sustaining, the energy released in the plasma (not counting that carried off by the neutrons) must be sufficient to maintain that temperature. Thus the reaction will be self-sustaining only above a certain critical temperature (the so-called "ignition temperature") which is about 400 million degrees for the D-D reaction and about 45 million degrees for the D-T reaction. (The curves are for plasma densities of about 10^{15} particles/cm^3.)

from constant collisions between rapidly moving charged particles, chiefly electrons colliding with ions. The rate at which energy is radiated by this process is found to vary with the square root of the temperature.*

Clearly, no isolated plasma can maintain high temperatures if it radiates energy away faster than it produces it. If the system is to be self-sustaining, the power P_g generated within the plasma must be greater than the power P_r that it radiates away.

As seen from Fig. 1–3, both P_g and P_r are increasing functions of the temperature. Fortunately, however, P_g increases more rapidly than P_r. As a result, a certain critical temperature will exist above which the reactions may be considered self-sustaining. In the case of the D-D reaction, this so-called "ignition temperature" is about 400,000,000°K. For D-T reactions, it is appreicably lower, of the order of 45,000,000°K.

High plasma purity

Another significant point, seen immediately from the equation for P_r, above, is that the presence in the plasma of any heavy nuclei (i.e., nuclei with high Z-values) will increase enormously the rate of energy radiation and correspondingly increase the critical temperature. This illustrates again the necessity for choosing as fuel a material with as low a Z-value as possible. Still more important, it illustrates the necessity for maintaining the plasma at high purity and of avoiding even minute amounts of heavy-nuclei contaminants.

Adequate confinement

A fifth (and major) requirement is to provide a suitable means of confining the hot plasma in a given region for a sufficiently long time

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* Power radiated by bremsstrahlung (P_r) may be shown by wave mechanics to be

$$P_r = 1.42 \times 10^{-27} Z^2 n_i n_e T^{1/2} \frac{\text{ergs}}{\text{cm}^3\text{-sec}},$$

where n_i and n_e are the number of nuclei and electrons per cubic centimeter, respectively, Z is the atomic number of the nuclei present, and T is the temperature (in degrees Kelvin).

For hydrogen isotopes, $n_i = n_e$ and $Z = 1$, and hence

$$P_r = 1.42 \times 10^{-27} n_i^2 T^{1/2} \frac{\text{ergs}}{\text{cm}^3\text{-sec}}.$$

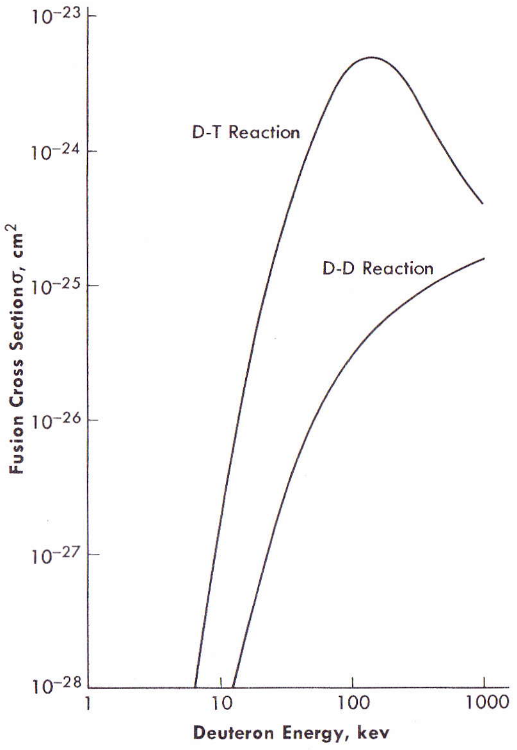

FIG. 1–4. FUSION CROSS SECTION VS. DEUTERON ENERGY. The variation in fusion cross section as a function of deuteron energy is shown for both the D-T and the D-D reactions. The probability of fusion is seen to be very small at low energies, but rises rapidly as the energy of the interacting particles increases toward 100 kev.

that an appreciable fraction of the nuclei may fuse together. At these high temperatures, the plasma nuclei move with enormous speeds and will travel many thousands of miles on the average before undergoing fusion.* Clearly the particles cannot be permitted simply to rebound back and forth between the walls of the vessel, for each collision would transfer energy to the walls. Interestingly enough, the problem is not so much that the walls would vaporize; with plasma densities in the range of 10^{14} to 10^{18} particles/cm^3, the energy content of the gas is actually too low to do much damage. Instead, the difficulty is that the plasma would be cooled as a result of its contact with the walls, and the reaction would be quenched. Some satisfactory method must therefore be found to confine the plasma particles to the interior of the vessel and to prevent them from striking its walls.

In the case of the sun and other enormous stellar bodies, forces of gravitation are effective in confining the plasma particles and in preventing their escape from the hot region. For laboratory experiments on Earth, however, gravitational forces are much too weak to be of practical value.

As will be seen in the next chaper, by far the most promising solution to the problem of particle containment appears to be the use of magnetic fields. Such fields can, in effect, exert a pressure on the charged particles of a plasma and may thus be used to "insulate" the walls of the vessel from the hot gas inside.

Even under optimum conditions, however, this insulation will be far from perfect, and after a limited period of confinement high-energy particles will penetrate through the magnetic field and escape. In a practical thermonuclear device, this period must be sufficiently long that the particles have a reasonable chance of undergoing fusion. A useful figure-of-merit in this respect is the quantity $n\tau$, where n is the plasma density and τ the period of confinement. It may be shown that for any practical fusion device using deuterium as fuel, the product $n\tau$ must be greater than about 10^{16} (where n is expressed in particles/cm^3 and τ in seconds). Thus, for a density of 10^{15} particles/cm^3, the period of confinement of individual particles must be 10 seconds or more. If the densities can be increased to 10^{18} particles/cm^3, a confinement time of one-hundredth of a second may be sufficient.

If a mixture of deuterium and tritium is used as fuel, the requirements are somewhat more relaxed. For this case, $n\tau$ must be greater than about 10^{14}, and the required periods of confinement are correspondingly reduced by a factor of about 100.

Development of useful power

A final requirement is to extract the energy released in the fusion process and convert it to useful power. If an equal mixture of deuterium and tritium is used as fuel, the great majority (80%) of the released energy appears as kinetic energy of the neutrons. To recover it, the neutrons must be slowed down in a suitable moderator outside the discharge chamber. The heat thereby generated in the moderator can be removed by a suitable coolant and used to generate electrical power through a heat cycle.

If deuterium alone is used as fuel, the picture is somewhat different. Here only about one-third of the released energy is transferred to the neutrons, the remainder going to the charged reaction products. If the magnetic field is sufficiently strong, these charged particles will be retained by the confining field, and their kinetic energy could, in principle, be transformed directly into electrical power.

There are a number of ways in which such a transformation could be envisaged. Imagine, for example, a plasma confined by a strong, externally generated magnetic field. If, now, the field strength were to be slightly increased, the plasma would be somewhat compressed and its density increased. Since the rate of power generation goes up with the square of the density (see page 8), the plasma temperature and pressure would rise rapidly, causing the plasma to expand against the magnetic confining field. The resultant variation in the magnetic field could in turn induce voltages in adjacent circuits and thus permit the direct generation of electricity.

However, this concept of direct power generation, while appealing in principle, may well be difficult or uneconomical in practice.

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* The average distance an ion will travel before undergoing fusion (generally called the "mean free path" for fusion and designated by λ) is given by the relationship $\lambda = 1/n\sigma$, where n is the particle density and σ is the cross section for fusion (see Fig. 1–4). For densities of 10^{15} particles/cm^3 and a cross section of 10^{-25} cm^2, λ is 100,000 kilometers.

RECAPITULATION

The major requirements of any controlled thermonuclear device may thus be summarized in the following way: one must (a) select a suitable fuel (such as deuterium, or a mixture of deuterium and tritium), (b) ionize and heat it to a temperature of a hundred million degrees or more, (c) confine the resulting plasma at this temperature long enough to allow a substantial portion of the nuclei to undergo fusion, and finally, (d) harness the released energy and convert it to usable power.

As we shall see in the forthcoming chapters, the problems associated with meeting these requirements are by no means trivial.

CHAPTER 2

THE PROBLEM OF CONFINEMENT

Early thoughts concerning fusion

In the United States, interest in the possibility of controlled fusion dates back even prior to the end of World War II. From 1944 to 1946, frequent and lively discussions of the subject were held among scientists assembled at the Los Alamos Scientific Laboratory—particularly E. Fermi, E. Teller, J. L. Tuck, S. Ulam, J. Wheeler, and R. R. Wilson. Most of the basic principles, if not already known, were formulated at that time, and a number of suggestions were made for achieving thermonuclear conditions.* While many of these suggestions were highly ingenious, all failed—for one subtle reason or another—to meet adequately the basic requirements of a controlled fusion device.

Need for magnetic confinement

One of the major stumbling blocks was finding a suitable method of plasma confinement. As indicated in Chapter 1, this complication arises from the fact that plasma particles will travel enormous distances, on the average, prior to undergoing fusion.

Of the many possible methods of plasma confinement, by far the most promising (if not the only) solution appears to be the use of magnetic fields.† Since magnetic fields, properly applied, may well provide the key to the achievement of controlled thermonuclear reactions, an elementary knowledge of the behavior of charged particles in such fields is essential to an understanding of the chapters which follow. A brief discussion of this matter is therefore presented here.

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* One concept, investigated theoretically by Tuck and Ulam, was to produce heating and (momentary) confinement of a deuterium plasma by causing jets of deuterium to collide at very high velocity. Attempts were even made, albeit unsuccessfully, to explore this concept experimentally.

† While not unequivocally ruled out, the use of electric fields for confinement does not appear to be feasible. The major deterring factor is that an electric field exerts oppositely directed forces on the electrons and positive ions of the plasma; if made to confine one component, the other would tend to escape. Another factor is the limited density achievable. Numerous proposals have been made for plasma confinement by electric fields, but none appears to have sufficient merit to warrant serious consideration. Other methods of confinement have also been suggested (see Appendix IV), but not found suitable for one reason or another.

Behavior of particles in a uniform magnetic field

Consider a group of charged particles in a vessel of some kind, as in Fig. 2–1(a). In the absence of a magnetic field, the particles will move in straight lines and immediately strike the walls of the vessel. If, however, a homogeneous (uniform) magnetic field is applied, as indicated in Fig. 2–1(b), the paths of these same particles will now be bent into tight helices encircling the lines of force of the magnetic field. As a result, the particles are not free to move across the magnetic field lines to the vessel walls; each is, in essence, "tied" to a line of force about which it revolves at a radius which depends inversely upon the magnetic field strength. The stronger the field, the smaller is the radius of curvature of the particle.

The only way now in which a particle can "diffuse" or move outward across the magnetic field is by means of a series of collisions with other particles; at each collision the particle's center of curvature may shift from one line of force to another, as shown in Fig. 2–1(c). The rate of diffusion across the magnetic field as a result of these collisions can be computed accurately. It turns out that the diffusion rate is inversely proportional to the square of the magnetic field strength (i.e., it varies as $1/B^2$, where B denotes the magnetic field strength). This relationship is extremely significant, for it shows that if a hot plasma is confined in a stable way by a magnetic field, the rate of particle diffusion toward the walls may be greatly reduced simply by increasing the strength of the magnetic field.

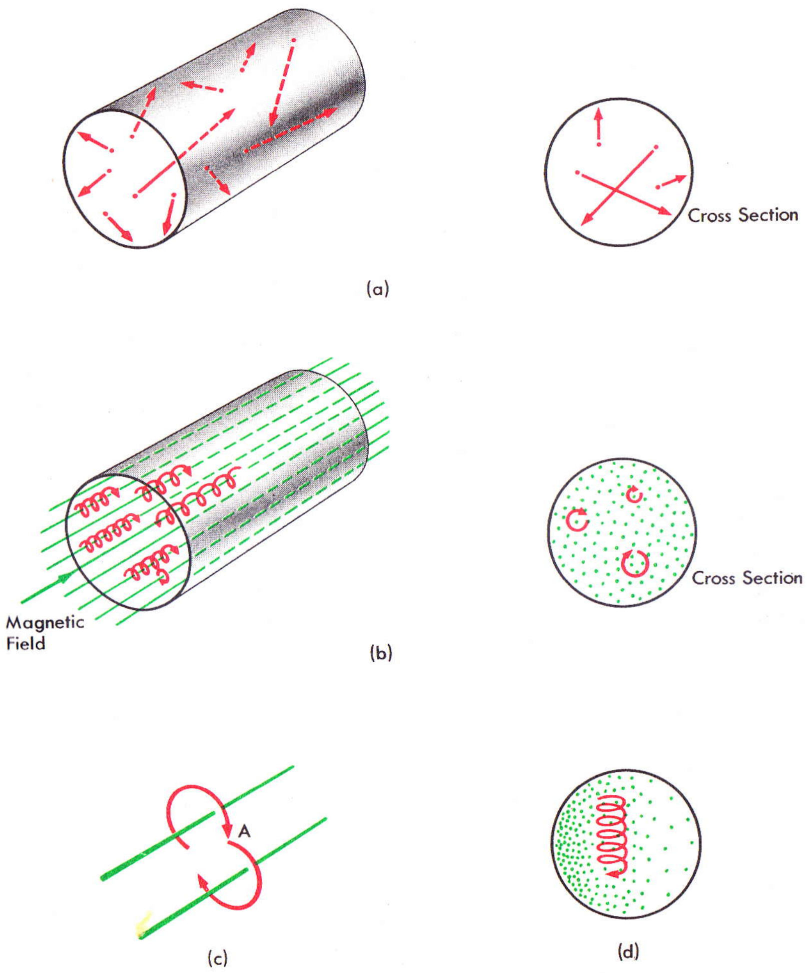

FIG. 2–1. EFFECT OF A MAGNETIC FIELD ON CHARGED PARTICLES. In (a), with no field present, the particles can move in straight lines to the walls of the vessel. In (b), with a homogeneous field parallel to the axis, each particle travels in a helical orbit encircling some line of magnetic field. It cannot move across the field toward the vessel walls except as a result of a series of collisions with other particles, such as shown in (c). Here, as a result of a collision at point A, the center of curvature of the particle may shift from one line of force to another. In (d) the motion of a particle in a nonhomogeneous magnetic field is shown. Because of the continual change in its radius of curvature, the particle will precess up or down, depending upon its charge.

The concept of magnetic pressure

From the above, it is seen that the presence of a magnetic field can act to confine a plasma within a given region and to impede the outward flow of plasma particles across the lines of force to the walls of the vessel. In essence, it may be considered as a means of exerting pressure directly upon the plasma. Under thermonuclear conditions, the plasma behaves much like an ordinary gas, and exerts an outward pressure whose magnitude increases directly with temperature and density in the usual way. If the plasma is to be confined, its outward pressure P_p must not exceed the inward pressure P_B which the magnetic field is capable of exerting* (see Fig. 2–2). The ratio of these two pressures will be denoted by the symbol β. With magnetic field strengths available in the laboratory, it is possible, in principle, to confine a gas at temperatures and densities which will yield significant amounts of power from the fusion reaction.

It is, however, essential to point out that if the mechanism of confinement is to be adequate, it must be a stable one. That is to say, it must not be possible for the plasma particles, acting collectively, to develop an instability that would permit them in some manner to push aside the magnetic lines of force and squirt rapidly to the walls of the vessel. From the outset of the program, there were indications that the success or failure of the Sherwood effort might well hinge on this question of stability.

Motion of particles in a nonuniform magnetic field

In preparation for later discussions, a brief comment should be made here concerning the behavior of charged particles in non-

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* Since the plasma acts like a normal gas, $P_p = nkT$, where n is the particle density, T is the temperature in °K, and k is Boltzmann's constant. The maximum inward pressure the magnetic field is capable of producing is given by $B^2/8\pi$, where B is the magnetic field strength in gauss. The ratio of these two pressures is denoted by β, where $\beta = nkT/(B^2/8\pi)$. This quantity will be used often throughout this book.

Since the rate of energy generation is proportional to n^2 (and hence to β^2 from the above relation), it is desirable to have as large a β-value as possible. The maximum value of β is 1; for this case, the diamagnetism of the plasma particles would exclude the confining field completely. (See Appendix I.)

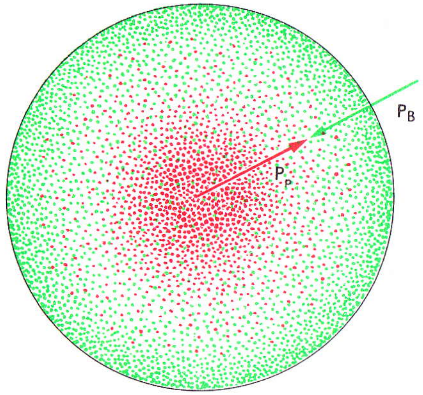

FIG. 2–2. BALANCE OF MAGNETIC AND PLASMA PRESSURES. The plasma behaves much like a normal gas, exerting an outward pressure $P_p = nkT$. If the plasma is to be confined, its outward pressure must be counterbalanced by an inward pressure of the magnetic field. The maximum pressure P_B that the magnetic field can exert is given by $B^2/8\pi$, where B is the field strength. The ratio of the two pressures is denoted by β.

uniform (nonhomogeneous) magnetic fields. Figure 2–1(d) shows in cross section a tube in which the magnetic field strength decreases from left to right. Now, a particle moving in a plane perpendicular to the magnetic field will no longer follow a simple circular path; because of the continual change in its radius of curvature, the particle will precess slowly upward or downward, depending upon its charge.

Problem of the ends; various U. S. approaches

The above discussions have considered only the motion of the charged particles *across* magnetic field lines. The motion of these particles *along* the lines of force, on the other hand, is completely unimpeded. Special configurations of the magnetic field must therefore be employed to prevent hot plasma particles from escaping out the ends of this route. A number of such configurations have been proposed, and they form the basis for the various approaches which have been pursued in the United States.

Specifically, the major experimental effort has been based upon three different methods of plasma confinement:

The pinch concept, in which the confining magnetic field is produced by *internal* currents within the plasma itself. Work on this concept has been carried out at the Los Alamos Scientific Laboratory* (LASL) in New Mexico, and at the University of California Radiation Laboratories (UCRL) in Livermore and Berkeley, California.

The stellarator concept, in which the plasma is confined in an endless tube (i.e., one which closes on itself) by means of an *externally imposed* magnetic field along its axis. The stellarator approach has been pursued at Princeton University in New Jersey.

The magnetic mirror concept, in which the plasma is confined in a *straight* tube by means of an externally imposed axial magnetic field, with magnetic mirrors to inhibit the loss of particles out the ends of the tube. This approach was developed initially at UCRL, Livermore, and has been subsequently incorporated to some extent in the programs at Los Alamos, at the Oak Ridge National Laboratory (ORNL) in Tennessee, at the Naval Research Laboratory (NRL) in Washington, D. C., and elsewhere.

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* An AEC laboratory operated by the University of California.

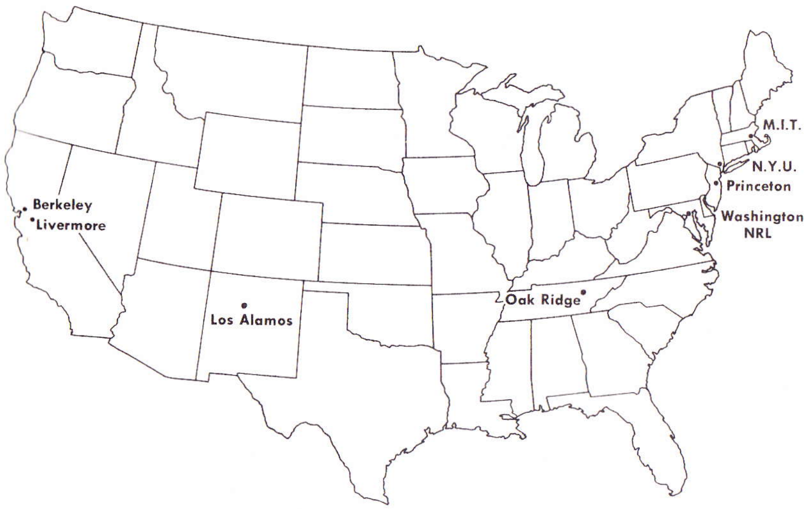


Fig. 2–3. Locations of Sherwood Activity.

In addition to the extensive work carried out on the approaches listed above, other methods of plasma confinement have been proposed and explored to a somewhat lesser extent, for example the cusped-geometry concept at Los Alamos and New York University, the astron concept at UCRL, and the rotating plasma concept at UCRL, Los Alamos, and Oak Ridge.

Each of these approaches will be described in some detail in the chapters that follow.

CHAPTER 3

THE PINCH PROGRAM (PART I)

A. From Inception to Mid-1953

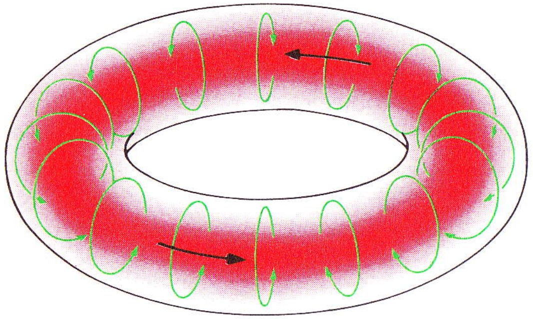
Basic principle of the pinch concept

The basic principle of the pinch approach is the interaction between a current in a gas and the magnetic field produced by this *same* current. This interaction may be seen as follows: suppose that a large current is induced in a gas in some suitable container, such as the toroid shown in Fig. 3–1. As the current builds up, it produces its own magnetic field, the lines of which encircle the current. This magnetic field, in turn, interacts with the fast-moving particles of the discharge, exerting on them an inwardly directed force which tends to make them constrict, or "pinch," to a dense, hot filament of current at the center of the tube.

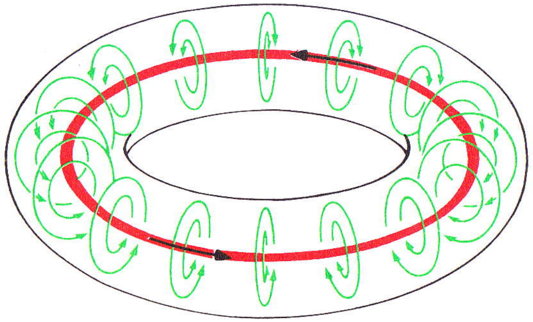
Early theoretical studies

Historically, the concept of the pinch effect in a plasma dates back to 1934, when W. H. Bennett published a theoretical paper in which he predicted the "self-focusing" or constriction of a stream of rapidly moving charged particles. Unfortunately, this work went almost unnoticed. It was followed in 1937 by an independent paper by L. Tonks, in which he predicted the same constriction, calling it the "pinch effect." Except for a related article in 1939 by Tonks and W. P. Allis, little attention was given this topic during the subsequent decade.

However, with the awakening of interest after the war in the possibility of achieving controlled fusion, a number of people recognized independently that the pinch concept might provide the ideal system of confining a plasma and heating it to high temperatures. The magnetic lines of force encircling the discharge should be effective in insulating the plasma particles from the walls of the discharge tube. In addition, the very process of current buildup and constriction could be expected to provide a method of heating the plasma. It



(a) Beginning of the Discharge



(b) Fully Formed Pinch

Fig. 3–1. The Pinch Effect. As current enters the tube under the influence of the voltage induced in it, an encircling magnetic field begins to form. This field exerts an inward force on the moving charged particles of the plasma, pinching them to the center of the tube and thereby tending to "insulate" the plasma from the walls of the tube. This compression also raises the plasma temperature.

seemed reasonable to hope that a pinched discharge might achieve high densities and temperatures to produce appreciable fusion of the plasma ions.

From simple theoretical considerations, however, it was clear that enormous currents (of the order of millions of amperes) would be required in order to achieve thermonuclear conditions.* Clearly, to produce and sustain currents of this magnitude *continuously* would be extremely difficult, if not impossible. It was, however, reasonable to think in terms of producing large currents *intermittently,* that is, in pulses which might last but a small fraction of a second.

Early experimental work

In any case, this approach seemed worthy of serious consideration. Indeed, experiments had been initiated in England during 1950 and 1951 by A. A. Ware, P. C. Thonemann, and others to investigate the mechanism of the pinch. Their results provided encouraging experimental evidence of the self-constricting properties of a high-current discharge.

In the United States, work on this concept was first undertaken by J. L. Tuck at Los Alamos. Tuck had long been intrigued by the possibility of controlled fusion and had continued to speculate on this

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* By balancing the outward gas pressure of the plasma against the confining pressure exerted inwardly by the self-magnetic field of the discharge, one may derive the following relationship:

$$\frac{1}{8\pi}\left(\frac{I}{5r}\right)^2 = nkT$$

or

$$I^2 = 200\pi r^2 nkT,$$

where I = the current in amperes, r = the radius of the pinch, n = density of particles in the pinch, T = temperature in °K, and k = Boltzmann's constant ($= 1.38 \times 10^{-16}$ erg/°K). If a is the cross section of the pinch ($= \pi r^2$), A the cross section of the discharge tube, and N the initial density before pinching, then $an = AN$, and

$$I^2 = 2.76 \times 10^{-14}\ ANT.$$

From this relationship, it is seen that in order to reach temperatures of, say, 10^8 °K under reasonable pinch conditions ($A = 400$ cm^2, $N = 10^{15}$ particles/cm^3) a pinch current of more than a million amperes is required.

subject as a sort of hobby. Early in 1952, he began a small experimental project to confirm and extend the published work of Ware.

The first experimental model, which Tuck characteristically called a Perhapsatron,* used a doughnut-shaped discharge chamber several feet in diameter. When a capacitor bank was discharged through a coil coupled to this toroid, a large pulse of current (tens of thousands of amperes) was induced in the gas contained in the chamber. The purpose of this experiment, which went into operation in the fall of 1952, was to create a highly ionized pinched discharge and study its properties.

Prediction of instability and subsequent verification

Even prior to its operation, however, theoretical studies carried out by M. D. Kruskal and M. Schwarzschild gave evidence of a severe impending difficulty. Working at Princeton, but with full knowledge of Tuck's activities, they succeeded in showing that a pinched discharge is subject to an inherent and violent instability. The way in which this instability arises is shown in Fig. 3–2. Suppose, for example, that a small kink should develop in the discharge. It is then seen that the density of magnetic field lines on the inside of the kink (the concave side) would become greater than that on the convex side, thereby producing a net magnetic force which would cause the kink to grow rapidly in magnitude. It would be expected, therefore, that the pinched plasma would shoot to the walls within just a few microseconds, dissipating part of its energy there and cooling the discharge.

The correctness of this ominous prediction was verified at Los Alamos shortly after the Perhapsatron was put into operation. Experiments showed that upon applying the voltage of the capacitor bank a brilliant discharge was produced in the toroidal tube, which rapidly contracted to a finely pinched filament of current at the center. No sooner had the pinch formed, however, than it disappeared, and the tube appeared to glow throughout its volume. To determine exactly what was happening, special "image-converter" cameras were used to photograph the discharge at any desired stage of development.* By taking a series of photographs at successively delayed instants of time, it was possible to observe the contraction of the discharge and the subsequent onset of kink instabilities which caused the discharge to thrash violently about the tube, dissipating its energy at the walls.

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* In response to a sceptic who, upon learning the ultimate purpose of the apparatus, laughingly called it an "impossibilitron."

Possible lines of attack

In spite of these discouraging results, interest in the pinch effect was by no means abandoned. The simplicity of the approach was very appealing, and there was hope that, by one means or another, a suitable solution to the problem would be found. There were, in fact, several possible alternatives which could be explored:

(a) One could seek some way of stabilizing the pinched discharge, that is, of preventing the onset of kink instability. If no suitable mechanism of stabilization could be found, then

(b) One could accept instability as a fact of life, and attempt instead to increase the temperature and density of the plasma as rapidly as possible to thermonuclear conditions. It seemed reasonable to think that if the plasma could be heated fast enough appreciable nuclear burning might be achieved prior to the onset of instabilities. If neither of the above alternatives was feasible, then

(c) One could investigate various modified pinch concepts which might not exhibit any tendency toward instability. One possible suggestion along this line was the concept of a "radiofrequency pinch," wherein the pinch might be produced (and possibly sustained) by the application of an alternating voltage of high frequency, rather than by the unidirectional voltage which had been applied in the first experiments.

Lack of adequate understanding

Serious consideration was actually given to all three of these alternatives. It was soon found, however, that the most serious impediment to progress was the lack of a clear understanding of the mechanism of the pinch process. No one really understood exactly how a pinch was formed.

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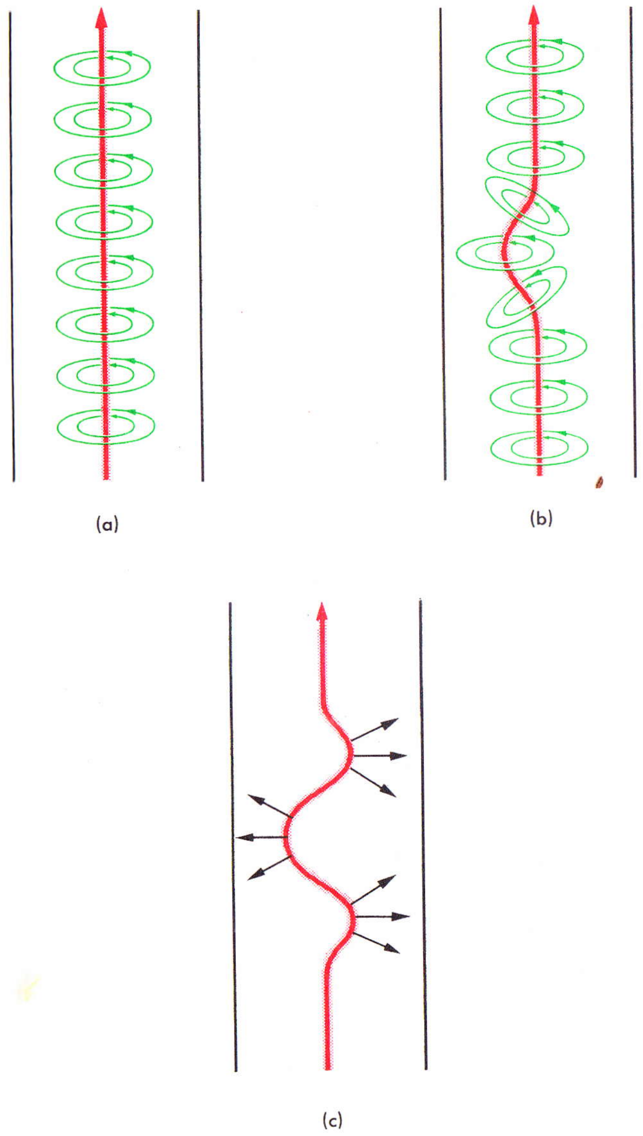
* See Chapter 8 for a brief discussion of methods of studying, or "diagnosing," the behavior of a plasma.



(a)

(b)

(c)

FIG. 3-2. KINK INSTABILITY. (a) Pinched filament prior to onset of instability. (b) If a small kink develops, the density of magnetic field lines on the inside of the kink is greater than that on the outside. (c) The resultant magnetic forces, shown schematically by arrows, tend to make the kink grow rapidly in size.

This lack of knowledge became critically evident when, in attempting to determine how to raise the temperature of the plasma more rapidly, it was found that the existing theory of the pinch was both inadequate and erroneous. According to the theory at that time, it was believed that the application of voltage around the discharge tube would result, as in an ordinary arc discharge, in the preferential acceleration (axially) of the electrons, and that the ions would be heated mainly by energy transferred to them by collisions with the more energetic electrons. Moreover, it was thought that the electrons, being more mobile, would respond much more rapidly to the presence of the magnetic field which they produced and would thus tend to contract first toward the center of the tube, dragging the ions after them by electrical forces of attraction.

Such a theory of heating and pinching was, however, completely incapable of explaining the experimental data obtained from the Perhapsatron. It was quite obvious that a better understanding of the basic principles was required before further progress could be made. Hence an intensive theoretical study of the pinch mechanism was undertaken. Little satisfactory progress was made, however, until mid-1954, when a new and beautifully simple theory of the formation of the pinch was advanced. (See page 29.)

B. Mid-1953 to End 1954

Attempts to stabilize the pinch

By the end of 1953, extensive experimental data on the pinch effect had been obtained with the Perhapsatron. The apparatus had been modified and improved and detailed studies of the pinch had been made for several gases of interest,* such as xenon, krypton, hydrogen, and deuterium. Instabilities, however, were continuing to cause concern, and considerable effort was devoted to finding means of stabilizing the pinch.

It had been recognized for some time that any tendency of the pinched plasma as a whole to displace itself away from the center of the tube could be counteracted by surrounding the glass walls of the discharge tube with a metal sheath. "Image currents" induced in the conducting sheath would produce forces tending to push the pinched plasma back to its central position. In a similar way, conducting walls would also be helpful in suppressing the growth of "gross" or "long wavelength" instabilities (e.g., broad kinks extending over an appreciable portion of the pinched discharge). The major problem lay in suppressing the "short wavelength" instabilities, (i.e., tightly bent kinks, smaller in size than the diameter of the tube). The conducting walls would be too remote from such kinks to be effective, and some other means of stabilization was required.

Several plausible suggestions were advanced for providing such stabilization. One of the more promising (proposed in late 1953 by J. L. Tuck and M. D. Kruskal, and independently by W. H. Bostick and M. A. Levine) was that the presence of a longitudinal magnetic field within the current discharge itself should have a stabilizing influence. Figuratively speaking, such fields would provide the pinch with a sort of "backbone" which might inhibit the formation of small kinks. A number of special cases were analyzed theoretically, involving longitudinal fields both inside and outside the pinched plasma. The results indicated that these fields should be partially effective in suppressing the instabilities, although not completely so.

To test these matters experimentally, several attempts were made with the Perhapsatron during 1954 to produce a partial stabilization with a pinched discharge containing an axial magnetic field. The outcome of these experiments was rather discouraging; in spite of the theoretical predictions, no evidence was found for an increase in the life of the pinch.

M-Theory of pinch formation

This disappointment was, however, more than offset by a development of major importance which occurred in mid-1954. As mentioned earlier, the achievement of higher plasma temperatures had been seriously hampered by lack of an adequate theory to explain the pinch process. The picture changed, however, when M. N. Rosenbluth, working at Los Alamos, proposed a new and simple theory of the formation of the pinch, based on the assumption that the plasma has a very high electrical conductivity. Conceptually, the so-called

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* In some experiments it is more convenient to use xenon or krypton (instead of the lighter gases), since they emit more light during the discharge and hence facilitate diagnostic studies.

"M-theory" of pinch formation may be explained in the following way. With high plasma conductivity, the sudden application of an axial electric voltage would produce a thin sheath of electric current at the outer surface of the plasma. In turn, the buildup of this current would produce an encircling magnetic "wall" which would contract rapidly toward the center of the discharge tube, driving electrons and ions ahead of it. Particles in front of the advancing magnetic wall would not be affected until it suddenly smashed into them; they would then rebound with twice the velocity of its advance. Clearly, the more rapidly the wall moved in, the higher would be the energy imparted to the particles in the impact. Rosenbluth derived a formula for the inward velocity of the magnetic wall and showed that it was directly proportional to the square root of the electric voltage gradient (i.e., the voltage per unit length) in the tube.

This simple theory provided an important new concept of the mechanism of plasma heating. If confirmed, it indicated that the ions were being subjected to a sudden acceleration in the radial direction and little if any acceleration in the axial direction. In addition, it provided an explicit expression for both the rate of contraction of the pinch and the plasma temperatures which should be produced, and predicted that the temperature could be increased at will simply by increasing the voltage gradient in the discharge tube. Finally, it indicated that, as a result of the impact of the magnetic wall, the energy imparted to the ions should exceed that imparted to the electrons (rather than vice versa, as expected from the earlier theory).

Impact of the M-theory

The impact of the M-theory on the pinch program was both immediate and far-reaching. For the first time, the experimental data from the Perhapsatron program began to be interpretable; a careful series of experiments carried out by J. A. Phillips and J. W. Mather showed close agreement between theoretical predictions and experimental observations.

With confirmation of the basic features of the new theory, thought was immediately given to steps that could be taken experimentally to increase the temperature of the plasma. According to the theory, the plasma temperature should be directly and linearly dependent upon the gradient of the electric voltage in the discharge tube. In the Perhapsatron, this gradient had been low (of the order of 20 volts/cm). Increasing it to the value needed to achieve thermonuclear temperatures (about 1000 volts/cm) clearly would require the construction of a new and complex apparatus, involving a major effort.

To obtain experimental information quickly, Tuck and his group turned their attention to the possibility of using a *straight* tube (instead of a toroid), in which a high voltage discharge would be produced between electrodes at its two ends.* The chief advantage of the straight tube was that high voltage gradients could be obtained much more easily. Moreover, it was reasoned that the ends of the tube should have very little influence on the temperatures achieved momentarily in the mid-section. According to the new theory, the force exerted during the pinch should be almost wholly in the radial direction, and the behavior of the particles in the middle should thus be unaffected by what happens at the ends.

The Columbus concept

The above plans were part of a tentative new philosophy which made its appearance at Los Alamos at that time. It was argued that, in spite of the instability difficulty, there still was a possibility, based on the dynamic pinch concept, of making a power-producing thermonuclear device.

The argument went as follows. A good figure of merit for a practical thermonuclear device is, as pointed out in Chapter 1, the quantity $n\tau$, where n is the plasma density and τ is the average confinement time. Under optimum operating conditions, $n\tau$ must exceed about 10^{16} for a deuterium fuel (or 10^{14} for a deuterium-tritium mixture). Now, the time for the pinch to disassemble (corresponding to the confinement time of the plasma) should be proportional to the diameter of the pinch. Thus, if τ could be made large enough (by making very large diameter pinches) and n large enough (by starting with sufficient gas in the tube), it should be possible, in principle, to exceed the break-even point. Calculations showed that heroic measures would be required to reach this goal. It would require pinches several meters in diameter, currents of hundreds of millions of amperes, and enormous voltage gradients. Also, the bursts of energy released from such pinches would be so large (equivalent to several tons of explosive) as scarcely to merit the term "controlled" thermonuclear reactions! Nevertheless, such were the extremes to which, in the absence of any better solution, the Los Alamos group was prepared to go if necessary.

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* The use of straight discharge tubes for producing pinches had been explored briefly in 1952 by W. Baker at UCRL, Berkeley (Chapter 6).

Experimental developments

As a first step toward this goal, a high priority was given to the design and construction of an experiment known as Columbus I, incorporating a straight discharge tube about 100 centimeters in length. A potential of 100,000 volts was to be applied between the ends of this tube, thus providing a voltage gradient of about 1000 volts/cm. Great care was taken to minimize the over-all inductance of the system, so that discharge currents of the order of a million amperes might be reached within just a microsecond or two. With this rapid buildup of current, it was expected that the temperatures and densities would be sufficient to produce detectable numbers of thermonuclear neutrons prior to breakup of the pinch through instabilities.

Simultaneously, but with much lower priority, work was begun on the design and construction of a rather sizable toroidal model also designed to operate with very high voltage gradients.

With the above developments, the outlook for the pinch program improved markedly. Even though the instability problem was still unsolved, the program seemed for the first time to be on firm theoretical ground, and the theory pointed the way toward the achievement of higher temperatures. Interest revived in this approach, and a small group under W. R. Baker at UCRL, Berkeley, picked up the trail. The encouraging results obtained from the programs at both Los Alamos and UCRL will be discussed in Chapter 10.

CHAPTER 4

THE STELLARATOR PROGRAM (PART I)

A. From Inception to Mid-1953

Origin of the effort

The Sherwood work at Princeton began in the spring of 1951. L. Spitzer, Jr., Professor of Astronomy at the University, had for several years been engaged in the study of very hot rarefied gases in interstellar space. In addition, he was working part time, under Atomic Energy Commission sponsorship, on a theoretical research study of the electrical and thermal conductivities of ionized gases.

Partly as a result of these interests and partly because of the intriguing but extravagant claims of R. Richter (in Argentina) of success in the controlled thermonuclear field, Spitzer was stimulated to consider possible ways of producing and confining high-temperature plasmas under controlled conditions.

Unaware of the pinch studies at Los Alamos, Spitzer conceived and developed a wholly different approach to the problem, in which the plasma would be confined in an endless tube by means of an *externally imposed* magnetic field. The evolution of this approach is outlined below.

Inability of the simple toroidal magnetic field to provide adequate confinement

It was recognized at an early date that the plasma could not be adequately confined by a simple axial magnetic field in the form of a torus. The reason for this is as follows. Consider a toroid wound externally with coils to provide an axial magnetic field configuration (see Fig. 4-1). An important characteristic of this configuration is the fact that each magnetic field line closes exactly on itself after one revolution—a fact described by saying that the lines of force are "degenerate." Because of the curvature of the torus, the magnetic field within it does not have the same strength everywhere but decreases in magnitude with distance from the major axis (line *CL*). This variation in magnetic field strength is indicated in the lower cross-sectional drawing. As a result of this nonhomogeneous field, the plasma particles do not follow simple helices about magnetic field lines; instead, they drift upward or downward, depending upon their charge. Electrons would, for example, drift downward and positive ions upward, producing an excess negative charge in the lower half of the torus and an excess positive charge in the upper half. The buildup of this charge separation would give rise to a strong electric field. The electric field, in turn, would tend to neutralize the confining effect of the magnetic field, thereby permitting the plasma particles to move freely outward and to strike the outer walls of the container. For these reasons, it was expected on theoretical grounds that an axial magnetic field of this type would not adequately confine a high-temperature plasma.

Development of the figure-8 configuration

Although recognizing the above difficulty, Spitzer wished, if possible, to retain the concept of an axial magnetic field in an endless tube, in order to prevent the escape of plasma particles along the lines of force. He thus sought some modification of the torus configuration that would prevent the buildup of the electric charge responsible for destroying its confinement.

From theoretical studies, Spitzer was able to show that a torus twisted into the form of a figure 8 would meet his requirements. Figure 4–2 illustrates a tube with this configuration, wound externally with current-carrying coils to provide an internal magnetic field along its minor axis.

The advantages of this modification are twofold:

(a) In the course of its spiraling motion along some line of force about the figure 8, a particle tending to drift upward at one of the curved ends (as a result of the nonhomogeneous field there) would tend to drift downward at the other end, since the curvature of the tube is in the opposite direction. While the net drift does not cancel out completely, it is very greatly reduced, and the resultant separation of charge is correspondingly much smaller in the figure-8 tube than in a torus.

(b) In addition, it may be shown that with the figure-8 configuration, the magnetic lines of force are no longer degenerate. In other words, a line of magnetic force, in passing about the tube, will *not*

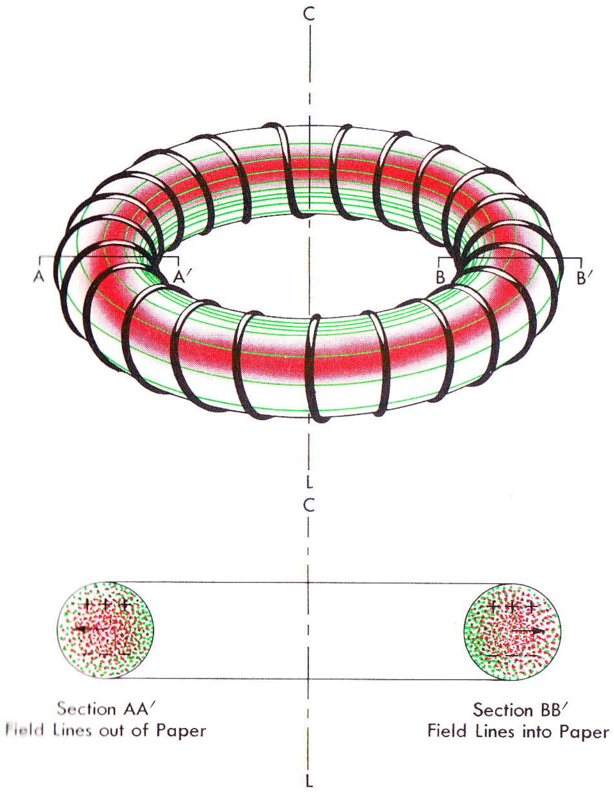

Fig. 4–1. Torus with an Internal Axial Magnetic Field, produced by external current-carrying field coils. A cross section of the torus is shown below. In this configuration, a separation of charge develops which permits the particles to escape to the vessel walls.

return exactly upon itself (as in the case of the torus), but instead will be somewhat displaced from its original position. If, for example, one were to follow the line of flux which passes through point A_1 in the cross-sectional drawing (Fig. 4–3), he would find that after one trip around the tube it would return to some point B_1; after a second trip it would pass through point C_1, and so on in rotational sequence about the tube. Thus the flux lines all rotate slowly about the magnetic axis of the tube. The magnitude of the flux rotation occurring after one transit of the tube (i.e., the magnitude of the rotational angle A_1OB_1) is determined by the twist associated with the figure-8 configuration. Accordingly, it is possible to design a twisted tube which will provide any desired rotational angle from 0° up to 180°.

This feature of "rotational transform" is of great importance, for it means that different regions around the magnetic axis O are interconnected by lines of flux. Since charged particles are free to travel *along* lines of flux without difficulty, this means that if a separation of charge were to begin to occur (as indicated in Fig. 4–2b), a current would develop between these two potentials, flowing through the stellarator tube *along* the lines of flux. Because of this possibility of charge neutralization, the electric potential in the curved region of the torus would be prevented from building up and destroying the confinement.

The figure-8 configuration thus appeared to offer a possible solution to the problem of plasma confinement at thermonuclear temperatures. Based around this idea, Spitzer developed conceptually the features of a continuously operating* full-scale thermonuclear reactor, fueled with a mixture of deuterium and tritium and capable of yielding a sizable net output of electrical power.

Initiation of theoretical studies

This concept, to which Spitzer gave the name "stellarator,"" appeared to him to merit serious consideration by the Atomic Energy Commission. He therefore contacted the AEC Division of Research, and a meeting was held on May 11, 1951, in Washington with some

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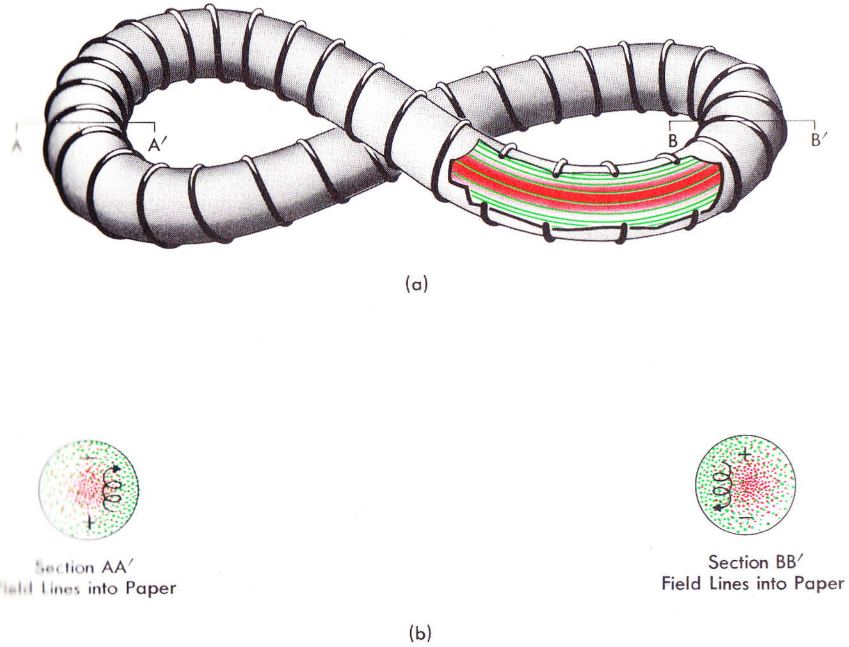
* As distinguished from the pulsed operation envisaged in the pinch effect.



(a)

(b)

Fig. 4–2. (a) A Figure-8 Stellarator Tube with external current-carrying coils to provide an axial magnetic field for confining the plasma. (b) Because of the twist of the tube, a charged particle precessing upward in the curved section at the left end will precess downward when it reaches the curved section at the right. Any separation of charge which tends to develop will now be canceled by current within the tube along the magnetic field lines.

of the Commission staff to consider his ideas in further detail. J. L. Tuck of Los Alamos was also present. While it was recognized that there were many problems (such as stability, mechanism of plasma heating, etc.) to be answered before its feasibility could be established, it was agreed that the stellarator concept as outlined by Spitzer was clearly of sufficient interest to warrant further study. At the suggestion of the Commission, Spitzer circulated a report on his ideas to designated scientists throughout the country for evaluation. In view of the favorable reception which this report received, a one-year study contract was authorized, beginning July 1, 1951, to investigate the theory of the stellarator concept in greater detail. Arrangements were made for the work to be carried out on a classified basis at the Project Matterhorn* facilities at Princeton.

After four months of study, a conference was held at Princeton on November 12, 1951, to evaluate the theoretical results and consider what the next step should be. In addition to the Princeton staff, representatives of a number of other AEC laboratories were present. The stellarator program was in general favorably received, and the results of the study were considered encouraging.

Model A stellarator

As a result of this November meeting and of further theoretical studies during the ensuing months, the scope of the contract with the Commission was appropriately modified, and a small figure-8 configuration was designed and built during 1952 under the direction of C. H. Willis. The primary purpose of this so-called "Model A" stellarator was to determine whether the new twisted configuration could really confine charged particles effectively.

In this model, a continuous magnetic field of up to 1000 gauss was provided by externally wound coils. The helium gas used in this model was partially ionized by inducing radiofrequency voltages

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* Project Matterhorn, which was organized at about this time, was primarily devoted at the outset to classified theoretical studies relating to the hydrogen bomb effort. Sponsored by the Los Alamos Scientific Laboratory, the work was carried out under the direction of J. Wheeler at the Forrestal Research Center near Princeton. The original work was discontinued in 1954, and since that time Project Matterhorn has been devoted entirely to the controlled thermonuclear program.

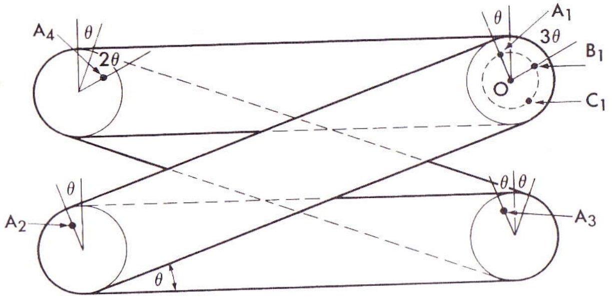

Fig. 4-3. End View of the Stellarator Tube, Showing the Property of Rotational Transform. Because of the twist of the tube, a line of force will no longer return on itself (as in the case of the torus), but will be displaced. A line of force passing through point A_1, for example, will consecutively pass through the points A_2, A_3, and A_4, and on returning to section 1, its position will have rotated to point B_1. Upon another transit of the tube, it will pass through C_1, the locus of these points being a circle. The angle of displacement (i.e., angle A_1OB_1) may be shown to be 4θ, where θ is the angle of inclination of the ends.

within the discharge tube, and measurements were made on the time of magnetic confinement of the electrons thus produced. The system could also be connected as a torus, with no rotational transform.

The results of the experiments, while puzzling in some respects, confirmed the theoretical prediction of improved confinement with a figure-8 configuration. There was, however, some indication that the rate of diffusion to the side walls was faster than would be expected from collision processes alone, and there was concern on the part of many that turbulence within the plasma might be carrying the particles to the outside walls faster than desired—in fact, at rates which would be intolerable in a full-scale device.

Initiation of work on Model B

Nevertheless, the results of the Model A stellarator were sufficiently encouraging to justify further experimental work, and the construction of a more advanced stellarator, designated as Model B, was initiated early in 1953. In addition to improved confinement resulting from stronger magnetic confining fields, a second method of plasma heating was to be incorporated; the plasma, after being partially ionized by a radiofrequency field, would be subjected to a unidirectional (direct current) pulse of voltage induced along the axis of the stellarator tube. This voltage would accelerate both the ions and electrons in an axial direction;* however, continuous collisions among the particles would rapidly randomize the imparted energy, thus raising the temperature of the plasma as a whole. With the so-called "DC pulse" method of heating, it was hoped to achieve a plasma temperature of some 200,000°K.

B. Mid-1953 to End 1954

Thoughts concerning larger models

During the latter part of 1953 and the first half of 1954, while the experimental group at Matterhorn was engaged in operating Model A and assembling the Model B stellarator, Spitzer looked ahead toward much larger devices. The succession of models was contemplated as follows: assuming the successful operation of Model B, the next major step would be to assemble a larger version (Model C), which would essentially be a pilot model of a full-scale power-producing prototype, called Model D. These letters were intended simply to denote major stages in the advancement of the program; it was recognized (and wisely so, as it turned out!) that the course of events might require additional intermediate models.

Before embarking on the design of the pilot model, it seemed reasonable to investigate first the characteristics of the Model D stellarator. Then, after having gained some insight regarding the size, field strength, and other properties of this full-scale prototype, it would be possible to design the intermediate device (Model C) in a more meaningful way.

Model D design studies

Since the group at Matterhorn was already overloaded with the existing program, it was felt desirable to draw upon industry for the loan of several qualified engineering physicists to undertake the conceptual design of Model D. Spitzer was therefore authorized to approach several top-management people with proper clearance at General Electric and Westinghouse and inform them of his program and need for obtaining industrial assistance for these studies. The response was immediate and enthusiastic. Each company offered to release two well-qualified men to the Matterhorn project on a full-time basis for a period of about nine months. General Electric furnished L. Tonks and W. Westendorp; and Westinghouse, W. Johnson and D. J. Grove. It was agreed that during this period these men would be working for the Commission rather than for their own companies, and that the classified information they gained from this work would not be channeled back into their companies.

During the next nine months, this four-man team worked at Princeton under the direction of Spitzer, with support as required from the growing theoretical group at Matterhorn. The task they set for themselves was a detailed study of the features and characteristics of a full-scale power-producing stellarator which might hopefully be of economic interest.

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* The voltage gradient, however, was to be kept low, so that the directed velocities of the particles would not be too much larger than their random (thermal) velocities. In addition, the externally applied magnetic field was kept large compared with the field produced by the current, so that no pinch resulted.

Several of the more significant of these features, namely "divertors" and lithium blankets, had been envisioned in Spitzer's original proposal to the AEC in 1951; others, such as "magnetic pumping" and "scallops," were modifications proposed by Spitzer in 1953 and 1954, respectively. Because of their importance in later discussions, these features will be described here briefly.

Need for a lithium blanket

As discussed in Chapter 1, in any thermonuclear reactor burning a mixture of deuterium and tritium, the neutrons carry off the great majority of the released energy. If this energy is to be put to practical use, the neutrons must be absorbed in a suitable moderator, and their kinetic energy converted into heat.

In addition, since tritium does not occur naturally in nature, the neutrons must be used to regenerate the tritium from lithium, by means of the reaction

$$n + Li^6 \rightarrow T + He^4 + 4.8 \text{ Mev}.$$

In this way, the tritium may be completely recovered. Thus, it acts as a sort of catalyst for the reaction, the fuel actually consumed being deuterium and lithium.

Both of the above requirements may be satisfied by surrounding the discharge tube with an annular "blanket," in which it would be possible to moderate the neutrons rapidly, capture them in lithium, and recover the tritium thereby produced.

In the Model D study project, much thought was given to the features of such a blanket. Since it would have to lie inside the heavy coils producing the confining magnetic field, a highly effective moderator would be needed to keep its thickness as small as possible. Consideration of the numerous alternatives led to the conclusion that the blanket should consist of a closely packed system of tubes, with water flowing through some and lithium in a suitable liquid form through others.* The heat generated in these liquids by the action of the neutrons would be transferred to external heat exchangers, connected in turn to conventional equipment for generating electric power. The lithium, in addition, would be circulated through a separate section designed to permit effective recovery of the minute amounts of tritium which it would contain. A study was made of all features of the blanket system, including such matters as the power required for pumping these liquids and effect of radiation damage by the neutrons.

Need for divertors

In controlled thermonuclear devices, there are essentially three ways in which energy may be transferred from the interior of the discharge tube to its walls or exterior:

(a) By the emission of radiation in the form of soft x-rays (bremsstrahlung) as a result of continuous collisions of the rapidly moving high-energy charged particles of the plasma. Under the operating conditions of a full-scale stellarator, roughly 5 percent of the total energy released would be in the form of such radiation.

(b) By the slow diffusion of energetic plasma particles outward across the confining magnetic field toward the walls of the discharge tube. In the case of a stellarator utilizing an equal mixture of deuterium and tritium, some 15 percent of the released energy would be carried away by these charged particles.

(c) By the emission of energetic thermonuclear neutrons, which would pass through the walls of the discharge tube and have to be captured in the region outside. About 80 percent of the released energy would be carried off in this form.

Spitzer had recognized from the outset that in a full-scale stellarator the walls of the discharge tube would be unable to withstand the energy impinging upon them from both the bremsstrahlung radiation and the outward-diffusing energetic particles. Even under optimum cooling conditions, the rate of heat transfer to the coolant would be too slow and the tube walls would vaporize. Accordingly, he had proposed modifying the stellarator so that the outward-diffusing particles would be prevented from reaching the main walls of the discharge tube, and be forced instead to dissipate their energy elsewhere. This modification, known as a "divertor," was analyzed in detail by the Model D study group.

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* Molten lithium was originally considered; from recent studies, liquid lithium nitrite appears more promising in many respects. The small fraction of neutrons lost (through absorption in structural materials or the nitrogen of the nitrite) can be compensated by (n, 2n) reactions in some material such as beryllium in the blanket.

In essence, a divertor consists of a large chamber encircling the stellarator tube at some convenient location and connected to it by a small opening (as shown schematically in cross section in Fig. 4–4). By means of a complex system of coils in the region of this opening, the lines of magnetic flux adjacent to the walls of the discharge tube are diverted through the opening and into the large chamber of the divertor. Charged particles of the plasma, diffusing slowly outward across the magnetic field, will eventually reach the outermost lines of magnetic flux and be diverted into this chamber, where they collide with the walls and give up their kinetic energy as heat. This chamber has a large wall surface, capable of being well cooled and of withstanding the enormous energy flow impinging upon it in the form of charged particles.

An additional important benefit to be anticipated from use of a divertor is the reduction of impurities emitted from the walls of the discharge tube. The outward-diffusing high energy ions (which in the absence of the divertor would eventually strike the tube walls, knocking neutral impurities back into the discharge) now give up their energy within the divertor chamber, and any neutral particles emitted in the process are quickly pumped away by large diffusion pumps attached to that region.

Need for magnetic pumping

A third important requirement of a full-scale stellarator is some means of heating the plasma to the required temperatures of a hundred million degrees or more. Spitzer showed, late in 1953, that the "DC pulse" method of heating would be incapable, even in large models, of heating the plasma to temperatures much above a million degrees. The major difficulty is the following. In this heating process, the axial electric field accelerates the electrons preferentially, and the electrons in turn heat the ions through collisions with them. As the temperature of the plasma increases, the probability of collision decreases, and the rate of energy transfer from electrons to ions drops off.

As a result, the electrons tend to "run away," that is, to increase rapidly in energy, while the energy (and temperature) of the ions is left far behind. An associated difficulty is that, as the temperature of the plasma increases, its electrical resistance drops off rapidly, and it becomes increasingly difficult to put energy into the plasma. The

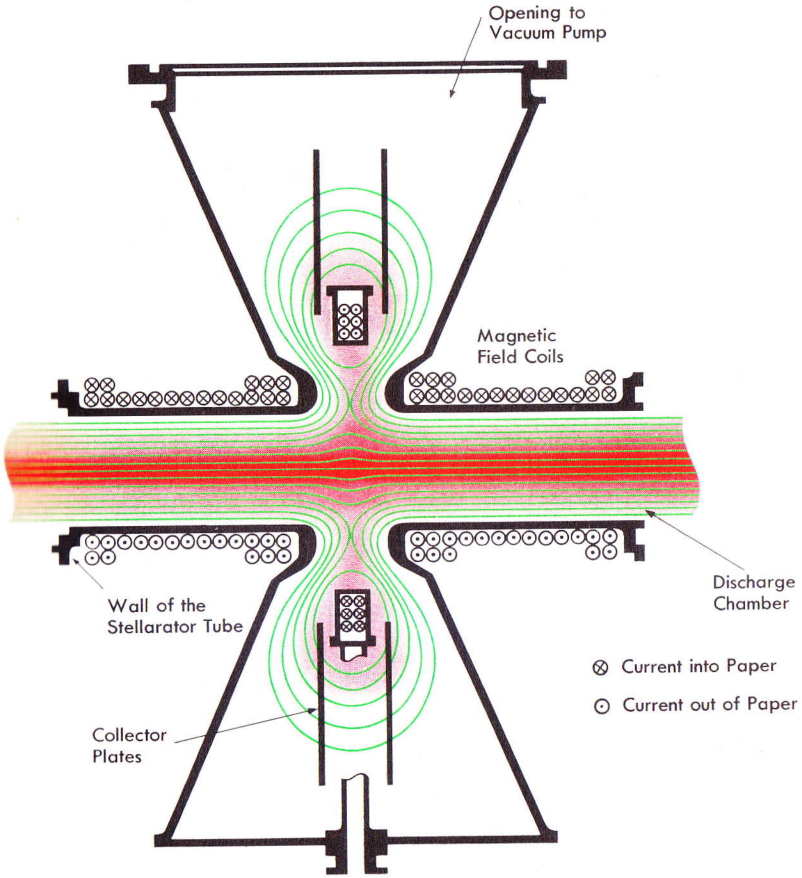

FIG. 4–4. DIVERTOR. Because of the magnetic field configuration in the divertor, charged plasma particles diffusing outward across the magnetic field will eventually be diverted into the chamber. Here, they collide with the walls, giving up their kinetic energy as heat.

DC pulse method of heating thus appeared to be limited in its applicability, and for temperatures above about one million degrees some new technique of heating had to be found. The most desirable scheme would be one by which the positive ions would be heated in preference to the electrons, since it is the *ion* temperature which determines the rate of the fusion process.

After much consideration, Spitzer proposed a method of heating which he called "magnetic pumping." In this method, the strength of the magnetic confining field would be alternately increased and decreased in rapid succession in one or more regions of the stellarator tube. The plasma in these regions would thus be successively compressed and expanded by a sort of pumping action. Theoretical study showed that by proper choice of pumping frequency, degree of modulation of the magnetic field, length of the tube over which it is imposed, and a number of other factors, the use of magnetic pumping should result not only in rapid heating of the plasma but also in preferential heating of the positive ions.

Need for scallops

One of the most important (in fact, nearly devastating) conclusions of the Model D study was that it would not be possible, using a simple figure-8 configuration, to achieve a *net* power yield from a full-scale stellarator, even under optimum conditions. The difficulty had its origin in the presence of current within the stellarator tube, as a result of charge separation in the curved regions (see page 34). It was shown that this current, in the direction of the lines of force within the tube, would provide an additional magnetic field that would distort the externally imposed confining field. In turn, this distortion would seriously decrease the value of pressure ratio β which might be achieved within the stellarator. Since the rate of energy generation is proportional to β^2 (see page 18), the resulting reduction in power would be intolerably great.*

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* It was shown that to keep the distortion from being excessive, β would have to be kept small compared with $8r/R$, where r is the radius of the discharge tube and R is the radius of curvature of the magnetic axis. Practically, this meant that β would have to be small compared with 0.1. Since the power generated varies with n^2 (and hence with β^2), such a low value of β would be intolerable.

A number of suggestions for overcoming this difficulty were investigated, but they proved for the most part to be impracticable. Finally, Spitzer proposed the introduction of so-called "scallops" into the curved portion of the stellarator tube, as shown schematically in Fig. 4–5. With a succession of curved sections having alternating curvature in the manner illustrated, the charge separation resulting from the curvature of the sections marked *a* would be almost wholly compensated by an equal but oppositely directed charge separation in the neighboring tubes, marked *b*. The slightly shorter length of tube *b* is compensated by an increase in its diameter. By means of this ingenious but complicating modification, the current in question could be limited to the curved U-bends of the stellarator tube. The current in the straight sections could thus be kept small, with the result that high β-values, and corresponding high power yields, could be achieved in these regions.

Design features of the Model D stellarator

As a result of detailed study of all the factors outlined above, the general design features of a full-scale stellarator slowly began to take shape. Designed for continuous (rather than pulsed) operation at a temperature of 200,000,000°K, it would have to be an enormous machine, more than 500 feet in length. The discharge tube, with a radius of $1\frac{1}{2}$ feet, would be surrounded by an annular moderating blanket 2 feet thick, which in turn would be encircled by an array of copper coils 4 feet thick to provide the magnetic confining field. The U-bends at the two ends would have the scallop configuration, and each would enclose a large divertor. In each of the straight sections there would be large magnetic pumping stations for raising the plasma temperatures to the ignition point. All in all, it was a sobering piece of equipment which would cost, exclusive of the turbogenerators, an estimated $200,000,000.* However, with a magnetic confining field of 75,000 gauss, it was estimated to be capable of providing a net electrical power output of some five million kilowatts.

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* Including turbogenerators and other conventional equipment, the total investment for a station of this size was estimated to be very close to one billion dollars.

The Model C stellarator

In spite of the awesome nature of the full-scale prototype, it was generally agreed that no insurmountable obstacles had been brought to light by the study. Admittedly, there were numerous engineering problems of great difficulty which needed to be solved. In addition, the big question was whether such a device could be operated in a quiescent manner, or whether instabilities would develop that would carry the plasma to the walls at a greater rate than could be tolerated. To this latter question there was no answer. It seemed to be an enormously complex matter. Among other things, there was reason to believe that instabilities would appear, if at all, only under conditions of high plasma density (i.e., only for rather large values of β). If so, experiments made with Model B could not be expected to bring these potential difficulties to light. It thus seemed appropriate to move ahead toward the conceptual design of the intermediate size Model C stellarator.

A small group at Princeton tackled this problem in the fall of 1954, with the goal of developing the preliminary design of a device which might serve not only as a pilot model for testing most of the features for the full-scale prototype, but also as a useful and flexible experimental tool for investigating the unknown problem of stability.

This study resulted in the preliminary design of a machine some 45 feet in length, having a discharge tube approximately 5 inches in radius. Plasma heating would be achieved by the application of three successive types of heating: radiofrequency, DC pulse, and magnetic pumping. Magnetic confining fields of 50,000 gauss would be provided on a pulsed basis for periods lasting as long as a second. Under these operating conditions, it was expected that temperatures of about 200,000,000°K could be achieved.

This conceptual design appeared sufficiently interesting and potentially important to be worthy of further design study. Since the Matterhorn staff was already overloaded, steps were taken to approach private industry for carrying out the detailed design of this rather large and complex model.

Experimental program: Models B-1 and B-2

In the meantime, the experimental group, working under the direction of J. A. Van Allen, was engaged in the assembly of the

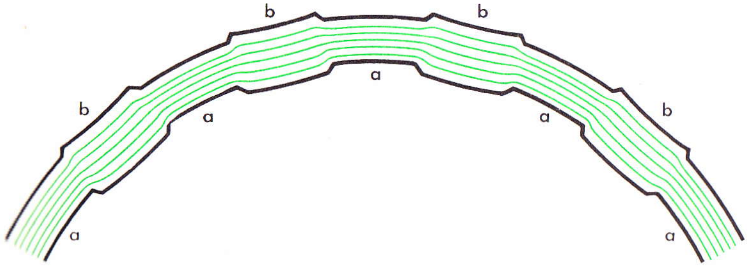

FIG. 4–5. SCALLOPS. The scalloped U-bends of the stellarator are composed of successive sections of alternate curvature, the purpose of which is to minimize the current in the straight sections of the stellarator and thereby increase the permissible value of β. The charge separation occurring in the sections marked *a* is compensated by an equal but oppositely directed charge separation in the tubes marked *b*. The shorter length of tube *b* is compensated by its greater diameter.

model B-1 stellarator, which went into operation in July, 1954. To avoid undue power consumption in the magnetic field coils, this model was designed for operation on a pulsed basis. The discharge of a capacitor bank through the externally wound coils was to provide an axial confining field of some 30,000 gauss for several milliseconds. When the strength of the magnetic field reached its peak, the heating pulse would be turned on, and measurements made to determine the temperature to which the plasma could be heated.

However, the group immediately ran into experimental difficulties. The pulse of current through the field coils produced strong forces which caused the coils to shift position slightly at each pulse. This shift, although small, was enough to cause a partial misalignment of the magnetic field, thereby seriously decreasing the effective volume of the tube. Attempts to rectify the difficulty with the existing coils proved to be only partly satisfactory, and extensive modifications were eventually required. During the brief periods of adequate alignment, however, spectroscopic and microwave measurements indicated that the plasma was being effectively heated to temperatures of the order of 100,000°K.

Even before the operation of the B-1 stellarator, consideration was being given to the possibility of incorporating in this model still another method of heating, namely, the method of magnetic pumping discussed on page 44. Calculations indicated that this addition should make it possible to achieve a temperature of several million degrees, even with a small model of this type. However, rather than delay operation of the B-1 stellarator, it was decided to expand the effort of the experimental group and build a second model (B-2), incorporating magnetic pumping. The construction of this device was started in mid-1954 by a group under N. W. Mather.

Hardly had the work gotten underway, however, when a new and ominous development threatened the entire stellarator approach. This development and its consequences are discussed in Chapter 9.

CHAPTER 5

THE MAGNETIC MIRROR PROGRAM (PART I)

A. FROM INCEPTION TO MID-1953

Origin of the program

News of the Sherwood developments at Los Alamos and Princeton was not long in reaching the University of California Radiation Laboratory (UCRL) at Livermore, where it aroused the interest and imagination of a number of scientists. Extensive discussions were held early in 1952 on the pinch and stellarator concepts; the problems associated with these approaches were analyzed in some detail and alternative solutions were sought.

In particular, there was concern on the part of H. F. York, Director of UCRL, Livermore, that while the figure-8 configuration of the stellarator provided an ingenious method of plasma confinement in an endless tube, the curvature of the U-bends would seriously limit the average value of β^* which could be achieved in such a device. In his view, the limitation on β might so reduce the net power output that this device could never be of economic interest. Instead of a configuration which closed on itself, York proposed the use of just a straight section of tube, again with an axial confining field, but with some suitable means of "stoppering" the ends to prevent plasma loss by this route. As a mechanism of stoppering, he suggested that it might be feasible to reflect the particles back toward the center of the discharge tube either by the pressure of microwave radiation, or possibly by "magnetic mirrors" at each end.

R. F. Post of the Livermore group offered to explore these suggestions, and a small group was set up under his direction to undertake theoretical and experimental studies on the problems of confining and heating a plasma in a configuration of this type. Of the alternative methods of stoppering the tube ends, the use of magnetic mirrors seemed the most promising. Post and his group set themselves the task of developing the theory of such mirrors, of determining the conditions under which the plasma particles would be reflected, and of calculating the rate of particle loss that might be anticipated. In addition, it was necessary to find a satisfactory method of heating a plasma, confined in this way, to thermonuclear temperatures.

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* For definition of β see footnote, page 18.

Magnetic field configuration

In the magnetic mirror approach, a straight section of tube is wound with external field coils so arranged as to produce an axial magnetic field which is weak in the central region, but strong at the two ends (as shown in Fig. 5–1). The strong fields at the ends constitute "magnetic mirrors," which tend to repel charged particles of the plasma and (under certain conditions) reflect them completely back toward the central region.

Conceptually, the action of the magnetic mirrors may be understood in the following way. Consider any charged particle spiraling in the central region under the influence of the magnetic field there. The motion of such a particle may be considered as having two components: an axial component of motion parallel to the magnetic field and a transverse component in a plane perpendicular to the magnetic field. The latter component, consisting of a circular motion of the charged particle about some line of force, gives the particle the properties of a small magnetic dipole, the strength of which is directly proportional to the kinetic energy of the particle in the transverse plane. In the central portion of the tube, where the field is homogeneous, this particle dipole may move freely along the lines of magnetic force. When, however, the particle approaches the region in which the magnetic field is strongly *non*homogeneous and increasing, it will always experience a force tending to return it to the weaker field in the central region (Fig. 5–2). Clearly, however, a particle having too great an energy in the axial direction (compared with its energy in the perpendicular plane) will not be turned back by the magnetic mirror fields, and it will be able to escape. Thus, if a group of particles is to be effectively confined by mirror geometry, it is essential that they be injected with low energy in the axial direction and high energy in the perpendicular plane. In addition, as one would expect, it is desirable that the magnetic field in

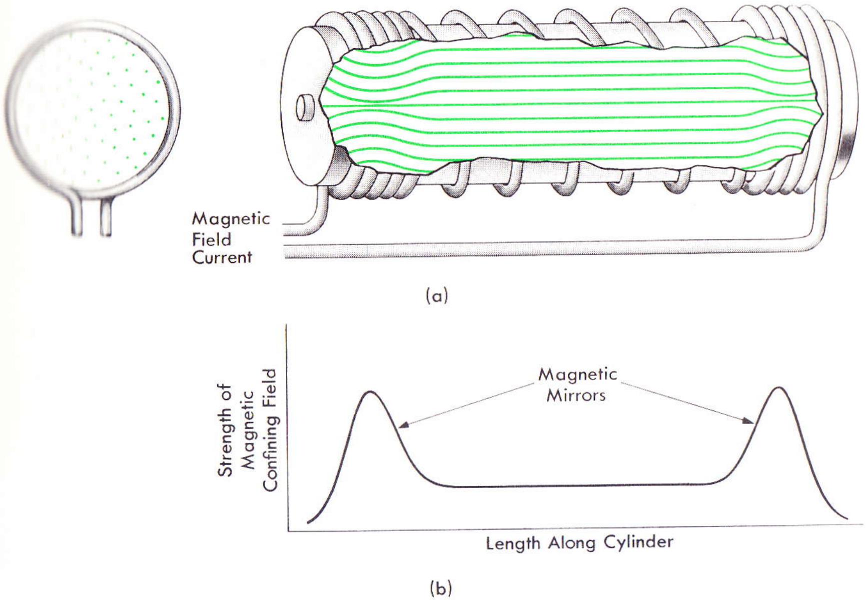

FIG. 5–1. MAGNETIC MIRROR SYSTEM. (a) Current-carrying coils around the cylindrical tube provide an axial magnetic field in the central region, with "magnetic mirrors" at the ends which reflect the plasma particles back toward the center. The variation in magnetic field strength along the tube is shown in (b).

the mirror region be as large as possible in comparison with that in the central region.*

Effect of collisions on plasma confinement

One of the complications in analyzing the magnetic mirror confinement of dense plasma is that the relative velocities of the particles in the axial and perpendicular directions change with time as a result of their collisions with one another. Consider, for example, a group of particles in the central magnetic field which initially have high velocities in the perpendicular plane and very low axial velocities. Under these conditions, they would find themselves reflected by any reasonable mirror field and thus wholly confined. As a result of collisions between these particles, however, their energy in the axial direction would slowly increase at the expense of their energy in the perpendicular plane, and particles would begin to escape through the mirrors.

Thus, the exact analysis of particle confinement in a mirror system is a complicated matter, depending upon many factors, such as particle densities, scattering cross sections, and initial energy distribution. However, the preliminary calculations carried out by Post and his group indicated that if a high-temperature plasma could be initially trapped in a suitable magnetic mirror system, there was a reasonable probability that the ions would undergo fusion before escaping through the mirrors. Consequently, a small experimental program based on this concept was thought worth while.

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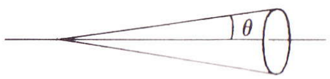
* Specifically, if $E_{\perp}$ is the energy of a particle in a plane perpendicular to the magnetic field and $E_{\parallel}$ its energy parallel thereto, then the particle will be reflected by a magnetic mirror if

$$\frac{E_{\parallel}}{E_{\perp}} \leq \left[\frac{B_m}{B_0} - 1\right],$$

where B_m and B_0 are the field strengths at the mirror and in the central region respectively. Expressed in another way, it may be seen that a particle will be able to escape through the mirrors if its E-vector lies in a cone (the so-called "escape cone") which has a half-angle θ given by

$$\theta = \sin^{-1}\sqrt{B_0/B_m}.$$



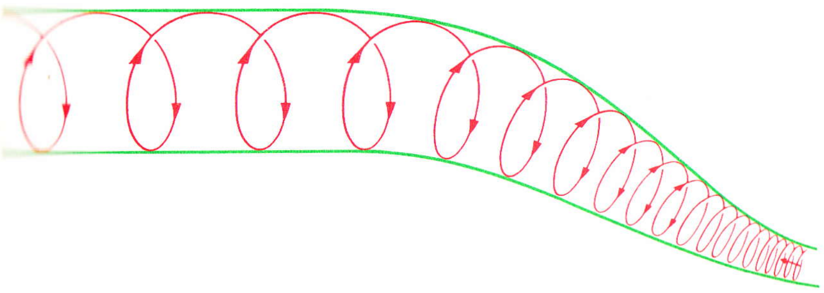


Fig. 5–2. Motion of a Charged Particle in a Magnetc Mirror System. As the particle winds into a tighter and faster helix, its forward motion is decelerated and finally brought to a halt. The particle is then reflected back into the central region whence it came.

Early experimental work

After some small exploratory experiments, an apparatus called "Albedo" was assembled late in 1952 to test experimentally the effectiveness of magnetic mirrors in reflecting individual charged particles. This experiment consisted of a straight section of evacuated tube, wound with coils to provide a rather weak axial magnetic field throughout its length and strong mirror fields at each end. A beam of low-energy ions was injected at one end along the central axis. Since these ions possessed only axial velocity (and hence no energy in the perpendicular plane), they passed readily through both mirrors and escaped through the far end. In order to trap some of them between the mirrors, a high-frequency electric field was applied to the particles as they passed slowly through the central region. This electric field accelerated the particles in the perpendicular plane, giving them sufficient transverse energy so that they could no longer escape.

The experiment showed that, once trapped, the particles were indeed effectively confined by this magnetic configuration, in accordance with theoretical predictions. The density of the trapped particles was so low that collisions among them were rare, and the particles would continue to bounce back and forth between the mirrors almost *ad infinitum*.

The problem of producing a high-density, high-temperature plasma

The effectiveness of magnetic mirrors for single-particle confinement having been experimentally confirmed, the next problem at hand was to determine the optimum method of producing a high-density, high-temperature plasma within a mirror system. Here two alternative possibilities suggested themselves:

(a) One could attempt to trap a rather dense plasma of *moderate* energy ions (a few kilovolts, or less) and then raise its temperature to high value, or

(b) One could attempt to trap a *low-density* beam of *high-energy* ions (i.e., with energies already corresponding, if randomized, to full thermonuclear temperatures), and then build up the resultant plasma density to values of practical interest.

As will be seen, both approaches, while straightforward in principle, proved to be extremely difficult in practice. In the latter case, for example, trapping a high-energy beam and building up the density of trapped particles would require a strong and steady magnetic field. The complication here is that when any particle is injected from some outside point into a static* magnetic field configuration, it will not be trapped unless its orbit is somehow changed (e.g., by a collision) while it is within the field. There appeared to be no easy way of producing such a change in state of the injected particles during their passage through the field.

Of the two alternatives, the first seemed the easier, and a suitable method was sought for successively producing, injecting, trapping, and heating a dense plasma of moderate energy ions in a magnetic mirror configuration. Clearly, the method which had been used in the Albedo experiment could not be adapted to the present needs. Aside from very low trapping efficiency, it was recognized that high-frequency electric fields could not penetrate the interior of a dense plasma, and their effect would thus be limited to the outer plasma surface.

Adiabatic compression

After considering a number of possibilities, Post proposed a method of heating known as "adiabatic compression." In this scheme, shown schematically in Fig. 5–3, the magnetic field strength of the entire configuration (i.e., of both the central region and the mirrors) is made to increase with time. From a source placed in the region of one of the mirrors, ions and electrons are injected transversely to the magnetic field at a time when the field strength is still low. As the magnetic field is increased, their transverse energy also increases, while their axial energy remains unchanged.

More specifically, if the magnetic field strength is increased by some factor over its value at the time of injection, the transverse energy of the particles is increased by exactly the same factor.†

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* I.e., one which does not vary with time.

† Mathematically stated, if B^i and B^f denote the initial and final values of the magnetic field strength, and $E^i_\perp$ and $E^f_\perp$ the initial and final values of the transverse energy, then

$$\frac{E^f_\perp}{E^i_\perp} = \frac{B^f}{B^i}.$$

Thus, if the particles are injected with a transverse energy of, say, 2 kev when the magnetic field is low (say 1000 gauss), increasing the field to 30,000 gauss will raise the particle energy to 60 kev, that is, to energies corresponding to thermonuclear temperatures. By this increase of the field it is possible first to trap the injected particles (as a result of increasing the ratio of $E_\perp$ to $E_\parallel$; see page 54), and subsequently to heat these particles to high temperatures.

Thoughts concerning a full-scale device

The above combination of techniques for confining and heating the plasma appeared to have the makings of a highly interesting approach to the problem of controlled fusion. With a straight discharge tube, it seemed reasonable to expect that (unlike the situation in the stellarator) the value of β could be high throughout the active volume of the tube. High β-values would imply the possibility of high power generation* per unit volume of plasma and hence the possibility of a more compact reactor than the stellarator, under the same operating conditions.

Looking into the distant future, an even more intriguing prospect was that if high β-values could be achieved, it might be possible to operate a full-scale device with the D-D reaction and still obtain a net power production. Such a goal, if feasible, was extremely interesting, not only because of its reliance on deuterium alone as the fuel, but also because of the possibility (as pointed out on page 13) of direct generation of electrical power. In this respect there was hope that, in the mirror type machine, it might even be possible to achieve appreciable nuclear burning of the He^3, which is formed as a product of the D-D reaction.

The total succession of the reactions would then be the following:

$$
\begin{array}{rl}
D + D & \longrightarrow He^3\ (0.8\ \text{Mev}) + n\ (2.4\ \text{Mev}) \\
D + D & \longrightarrow T\ (1.0\ \text{Mev}) + p\ (3.0\ \text{Mev}) \\
T + D & \longrightarrow He^4\ (3.5\ \text{Mev}) + n\ (14.1\ \text{Mev}) \\
He^3 + D & \longrightarrow He^4\ (3.6\ \text{Mev}) + p\ (14.7\ \text{Mev}) \\
\hline
6D & \longrightarrow 2\ He^4\ (7.1\ \text{Mev}) + 2\ p\ (17.7)\ \text{Mev} + 2\ n\ (16.5\ \text{Mev})
\end{array}
$$

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* The power generated, P_g, is proportional to n^2 and hence to β^2, since β is defined as $nkT/(B^2/8\pi)$.

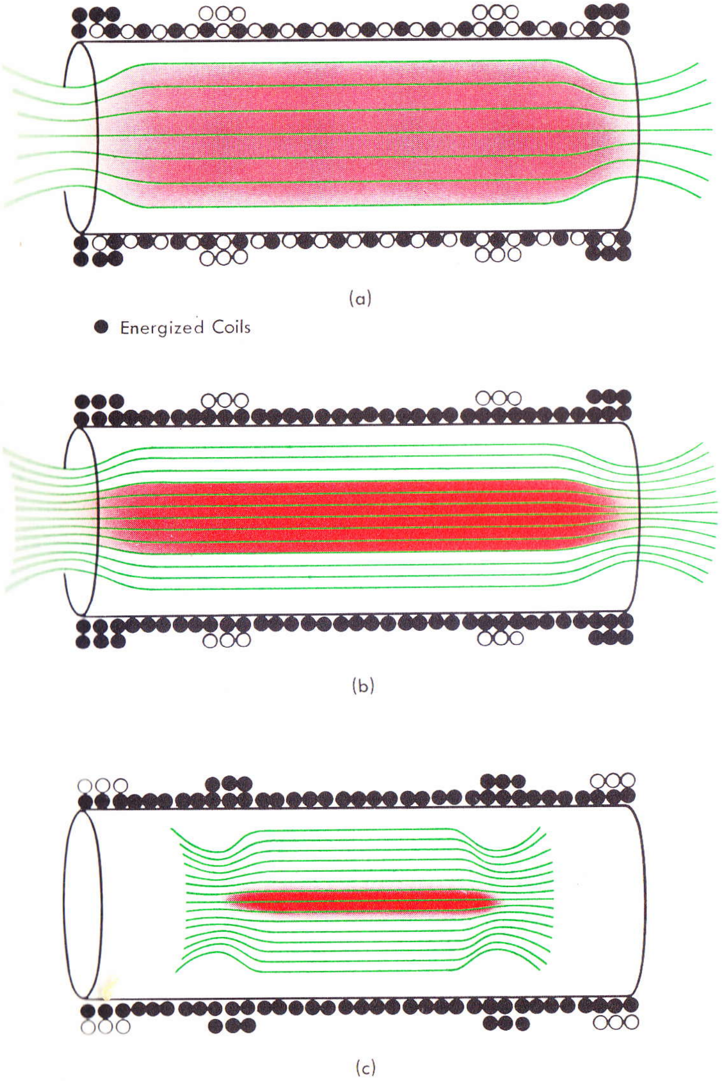

FIG. 5-3. ADIABATIC COMPRESSION OF THE PLASMA. (a) Plasma is injected into the chamber while the field is weak. (b) The magnetic field strength is then increased, compressing the plasma toward the center and raising its temperature. (c) The magnetic mirrors may also be moved axially inward to provide additional compression and further increase in temperature.

With complete nuclear burning in this way, some 60 percent of the total energy released would be in the form of charged particles. If these particles could be effectively confined by the magnetic field, most of the released energy might then be converted directly into electrical power, with high over-all efficiency.

Need for very high temperature

It was recognized, however, that the desire to operate on the D-D cycle, with appreciable burning of the He^3, would require substantially higher temperatures than those contemplated in the stellarator. In addition, there was still another reason why extremely high temperatures would be required: in the magnetic mirror approach (in contrast with the other concepts) it is clearly important that a significant fraction of the nuclei undergo nuclear fusion *prior* to their motion becoming completely randomized; otherwise there would be an excessive loss of hot but unburned fuel out through the mirrors. To increase the likelihood of their fusing prior to being scattered out the mirrors, the particles would have to have temperatures not far below the maximum of the D-D cross-section curve (see Fig. 1–4).

Recapitulation; work on the Table Top Model

Recapitulating briefly, the concept evolved was that of an ultimate machine which hopefully might use deuterium as fuel and operate on a pulsed basis somewhat similar to a diesel engine. A plasma of medium-energy deuterons and electrons would be injected into the discharge chamber while the confining field was still weak; the rising field would then trap and heat the plasma by adiabatic compression to temperatures of nearly a billion degrees; in the process the plasma would be compressed toward the center of the discharge tube. Still further increases in density and temperature could be provided by moving the mirrors axially inward. Prior to complete randomization of the initially directed motion of the plasma particles, appreciable burning of the fuel ions would occur, with energy released largely in the form of charged particles which would be confined by the strong magnetic field. To complete the cycle, the above compression operation would be reversed; the hot plasma would then be permitted to expand against the magnetic field, producing electrical power directly in external circuits. The above concept was admittedly looking far into the distant future. It nevertheless set a possible goal toward which one might begin to move.

As a first step toward a study of magnetic compression pressure, work was started during 1953 on an experimental model known as "Table Top." This model, having a cylindrical discharge chamber some 4 feet in length and 6 inches in diameter, was designed to operate with a pulsed mirror field rising to 20,000 gauss in the central region. The ion source for the experiment was to be a so-called "titanium source," consisting of a piece of titanium metal onto which deuterium gas is adsorbed. By suddenly heating the titanium, a burst of electrons and deuterium ions could be released at any predetermined moment into the discharge chamber.

B. MID-1953 TO END 1954

Difficulties encountered

During this next period, a number of problems were encountered in the development of the magnetic mirror approach. On the theoretical side, increasingly detailed study was made of the process of trapping, heating, and confining a plasma in magnetic mirror geometry. While in general the results were encouraging, there were still many unknown factors, the importance of which was difficult to judge. Among them was the problem of estimating the rate at which the ions of a dense hot plasma would be lost through the mirrors prior to undergoing fusion. There was, in fact, concern on the part of some theorists that this rate might be too high to permit the magnetic mirror approach to be of eventual practical interest.

On the experimental side, a subgroup headed by F. C. Ford worked rapidly toward the completion of the Table Top model and the assembly of the necessary diagnostic equipment for testing its operation. Even before completion, however, it became increasingly clear that the titanium ion source which was to be used in this model would not work effectively in the presence of a magnetic field. Further investigation indicated, in fact, that the development of a really satisfactory ion source might be much more difficult than had been anticipated.

Requirements for an effective ion source

The problems involved in the development of an effective source for this purpose were multifold. In the first place, it is desirable for the source to have as large an emission of positive ions as possible, since the active volume of the chamber must be filled with an initial density approaching 10^{13} ions/cm^3, and the period available for injection is very short. Second, the energy of the ions at time of injection must be reasonably high (of the order of 1 kilovolt or more) so that their final energy after adiabatic compression will be sufficient to produce copious thermonuclear reactions. Third, there are rather stringent limitations on the angle of injection if the particles are to be adequately trapped between the mirrors by the rising magnetic field. Fourth, to avoid problems of space charge it is essential that the injected ions be completely neutralized, that is, that they be accompanied by an equal number of free electrons. And fifth, it is important that the source not inject appreciable quantities either of impurities or of un-ionized particles into the chamber, since the former greatly increase the radiation losses, and the latter permit the loss of energetic ions from the plasma by the mechanism of charge exchange.*

Satisfying any one of the above requirements appeared difficult; satisfying all of them simultaneously appeared to be a problem of major stature, particularly in view of the severe limitations in the injector size that were imposed by the smallness of the experimental model. The deuterium-loaded titanium sources first used in Table Top yielded ions with disappointingly low energies when operated in a magnetic field; furthermore, there was appreciable contamination of the beam by titanium ions and neutral deuterium atoms. Nevertheless, because of its convenient size, this type of source offered the best promise as a pulsed-type injector for small experimental models, and work was accordingly initiated at UCRL to develop an improved version with higher energy output.

Continuous ion source

It was recognized, however, that the titanium-type ion source provided only a temporary solution to the injection problem. Its many limitations (particularly its limited gas emission) made it unsuitable for use in larger devices. Larger machines would clearly require a reliable source which could provide an intense and uncontaminated beam of energetic ions on a continuous (rather than a pulsed) basis.

Ion sources possessing many of these characteristics had already been developed at UCRL and Oak Ridge during the Second World War for use in electromagnetic separation of isotopes. These so-called "Calutron" sources were, however, far too large for use as injectors in magnetic mirror machines of the size under consideration. Furthermore, it was not at all certain that they could be made to operate properly in the complex and nonhomogeneous fields characteristic of these machines.

However, in view of the increasingly critical need for suitable injectors, the Oak Ridge National Laboratory was encouraged to develop a modified Calutron-type source for use in the magnetic mirror program. A series of meetings was held with representatives of both laboratories, and the requirements of the Mirror group were specified. The admittedly difficult goal was to develop an Oak Ridge type source which might even be small enough to be used in the Table Top machine.

Toy Top Model

While this developmental work was underway, it was decided, partly to compensate for the low energy of the ions available from titanium sources and partly to give information on the strength of field coils, to build a small experimental model capable of achieving extremely high magnetic fields. In this so-called "Toy Top" experiment, carried out largely by F. H. Coensgen, the heart of the apparatus consisted of a magnetic field coil the size of a man's hand, connected to capacitor banks and electrical switching equipment filling several rooms. In a number of early experiments, the enormous magnetic forces associated with the sudden discharge of some 50,000 joules into the windings destroyed or badly twisted the coils. Eventually, however, improved coils were built which were capable of producing and withstanding pulsed field strengths of the order of 200,000 gauss at their center, with mirror fields of the order of 300,000 gauss. Titanium plasma sources then on hand were used as injectors for this

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* For a discussion of charge exchange, see page 66.

Toy Top model. In spite of the low energy of the plasma ions emitted by this source, it was hoped that the enormous increase in magnetic field strength would produce the temperatures and densities necessary for thermonuclear reactions. Indeed, there was strong evidence of plasma heating with this model; measurements gave conclusive evidence that the process of adiabatic compression was effective in increasing the transverse energy of the particles roughly in accordance with the theory. Unfortunately, however, the other inadequacies of the ion source proved to be overriding, and neutrons were never reliably observed from the experiment.

By this time, in mid-1954, storm clouds were already beginning to gather for a new impending difficulty: instabilities. The origin of this difficulty and the resultant impact on the magnetic mirror program will be discussed in Chapter 9.

CHAPTER 6

DEVELOPMENT OF OTHER PROJECTS (PART I)

In addition to the three major projects described in preceding chapters, a number of other developments of importance to the Sherwood program occurred before the end of 1954. Some of the more significant of these are discussed below.

At Oak Ridge

At the Oak Ridge National Laboratory (ORNL), a small group with extensive experience in ion-source technology became interested in participating in the controlled fusion field. Under the direction of E. D. Shipley, theoretical studies were initiated in the latter part of 1952 and later supplemented by an experimental investigation of several topics of general interest to the Sherwood effort.

Rate of plasma diffusion in a magnetic field

One of the most crucial problems in the Sherwood effort was the question of how fast the plasma ions would diffuse across the confining magnetic field. The simple theory of diffusion predicted that the rate should be inversely proportional to the square of the field strength (that is, to $1/B^2$). Under such conditions, it was not difficult to show that the rate of loss of hot particles by this route could be kept to tolerable values by applying strong but achievable magnetic fields.

However, the only available *experimental* data on this subject, acquired during World War II, had given results sharply in conflict with the above theory. According to the interpretation given by D. Bohm, the experiments indicated that plasma oscillations were the mechanism principally responsible for ion diffusion across magnetic fields and that the rate of diffusion was inversely proportional to the first power of B (that is, to $1/B$). If true, this result implied that very much stronger magnetic fields would be required to keep the outward diffusion of the plasma within permissible limits.

Such enormously strong fields, if they could be produced at all, would require so much power input that it was questionable whether, in these circumstances, a controlled thermonuclear device could ever be a net power producer.

It was thus of critical importance to the Sherwood Program to resolve the discrepancy and make a reliable determination of the rate of diffusion of a plasma in a magnetic field, both in the presence and in the absence of plasma oscillations.

This task was undertaken at the Oak Ridge National Laboratory in the summer of 1953 by A. Simon and R. V. Neidigh. A lengthy series of experiments was carried out under conditions both similar to and differing from the earlier work of Bohm and group. While the results were initially perplexing,* strong evidence was accumulated in support of a $1/B^2$ dependence. In view of its importance to the future of the controlled thermonuclear program, it can be imagined that this encouraging evidence was heartily welcomed.

Study of the charge-exchange process

Another project of general interest to the Sherwood field was the measurement, carried out particularly by P. M. Stier and C. F. Barnett, of the cross section for various charge-exchange reactions. The process of charge exchange had long been recognized as a serious mechanism of loss of hot plasma particles from the discharge. As an example of the way in which this could occur, a cold neutral particle—a hydrogen atom, say, coming from the walls of the chamber—could wander slowly into the center of the discharge and transfer its electron to a hot plasma ion. The reaction involved may be indicated in the following way:

$$(H^0)_{\text{cold}} + (H^+)_{\text{hot}} \rightarrow (H^+)_{\text{cold}} + (H^0)_{\text{hot}}.$$

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* Among the perplexing features was the fact that for a given magnetic field strength the magnitude of the diffusion coefficient was still considerably larger than that which would be expected from ordinary collision diffusion theory. This result has been shown to be a direct consequence of the finite size of the experimental apparatus and is in accord with the theory. There is reason to believe that in an endless tube such as a torus or a figure 8 the actual value of the diffusion coefficient would be identical with the theoretical value.

The hot ion thus would become a neutral particle and escape immediately through the confining magnetic field, dumping its energy at the walls of the chamber and possibly knocking out other cold neutral particles in the process.

Since the probability of a charge-exchange reaction of this type may be extremely large (of the order of a hundred million times that for fusion), it is clear that the number of neutrals which can be tolerated in the hot plasma is exceedingly small. This is one reason why very clean vacuum systems are required—systems with negligible amounts of adsorbed gases on their surfaces which could release cold neutral particles under bombardment.

Ion-source work; concentric arcs

Still another important activity at Oak Ridge was the work carried out on ion-source development. In addition to designing and building the injector for use at Livermore (see page 62), the group gave a great deal of thought to completely different methods of injection and heating which might be used, with either stellarator or magnetic-mirror type confinement, to produce thermonuclear conditions directly.

One of the more interesting concepts, developed primarily by L. P. Smith and J. S. Luce, involved the use of arc discharges along an axial magnetic field, with an electric voltage applied across the field. In one version, shown in Fig. 6–1(a), a deuterium arc was formed along the axis of a cylinder within which existed a strong axial magnetic field. The application of a large negative voltage (30 kilovolts, say) to the concentric cylinder would draw deuterons out of the low-energy arc and accelerate them toward the outer cylinder. Because of the action of the magnetic field, the particles would turn around and decelerate as they returned to the central arc. Thus an annular ring near the outer cylinder would be filled with ions having energies sufficiently high to undergo thermonuclear reactions. Losses of ions out the ends would be minimized by the use of magnetic mirrors or an endless tube.

In a modified version of this concept (Fig. 6–1b), the configuration was essentially turned "inside out": (1) the concentric metal cylinder was replaced by a cylindrical deuterium arc which served as a source of low-energy deuterons, and (2) an arc at the axis, held at a large negative potential, provided an inward acceleration of the deuterons. The advantage of this modified version was that it provided greater density of the energetic ions in the central portion of the cylinder.

Rather extensive experimental work was carried out on these various arc concepts. Neutrons were produced with the discharge of Fig. 6–1(a), and the experiment indicated that they came from the gas between the arc and the cylinder. While numerous difficulties were encountered, particularly with regard to preventing breakdown in regions external to the operating volume, the concept appeared promising in many respects. Indeed, it provided the basis for some of the work carried out later on rotating plasmas (see page 127).

AT THE UNIVERSITY OF CALIFORNIA

In addition to the magnetic mirror program already under way, several new projects were started prior to or during 1954 at the UCRL laboratories in Berkeley and Livermore: namely, the work of W. R. Baker on the pinch effect and that of S. A. Colgate on a project known as "Collapse." These projects are discussed briefly below. To coordinate and speed the progress of the Sherwood effort, the over-all program at both laboratories was placed under the direction of C. M. Van Atta early in 1954.

Pinch work at UCRL, Berkeley

In the spring of 1952, W. R. Baker of UCRL, Berkeley, became intrigued by the Los Alamos work on the pinch effect and revived some of his earlier work on discharges in hydrogen tubes. By producing a large pulsed current discharge in a straight discharge chamber, Baker obtained clear photographic evidence that the current was being pinched toward the center of the tube. However, since it was believed that the new Livermore laboratory would assume full responsibility for the Sherwood program at UCRL, the work was dropped after several months and not resumed until the end of 1954, at which time a more intense effort was made to develop the pinch approach. This later work is discussed in Chapter 10.

Shock-heating; "Collapse"

During 1954, S. Colgate instituted a program at UCRL, Livermore, to investigate the feasibility of shock-heating a plasma to

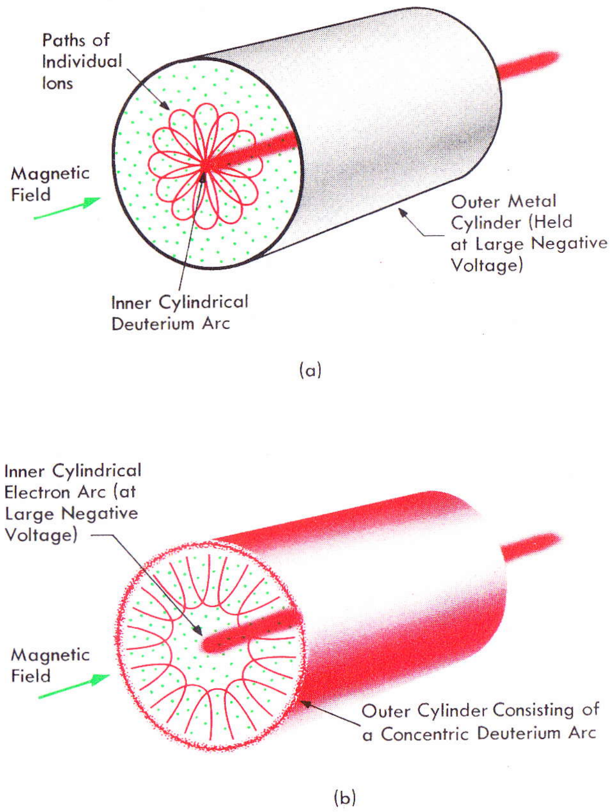

Paths of Individual Ions
Magnetic Field
Outer Metal Cylinder (Held at Large Negative Voltage)
Inner Cylindrical Deuterium Arc
(a)
Inner Cylindrical Electron Arc (at Large Negative Voltage)
Magnetic Field
Outer Cylinder Consisting of a Concentric Deuterium Arc
(b)

FIG. 6–1. CONCENTRIC ARC SYSTEM. The metal cylinder in (a) is held at a high negative potential, causing deuterons from the arc to accelerate toward it. Because of the magnetic field, however, the deuterons turn around and decelerate back to the central arc. Near the outer cylinder, the ions have energies high enough to undergo fusion. (b) In this modified version, a cylindrical arc of low-energy deuterons is formed parallel to the magnetic field with an arc along its axis held at a high negative potential. This arc causes the deuterons to accelerate toward the axis, giving a concentration of energetic ions in the central region of the cylinder.

thermonuclear temperatures using a magnetic field configuration essentially the inverse of that for the pinch. This configuration can be created by producing a very sudden discharge of current through a conducting sheet wrapped around the discharge tube, in the manner shown in Fig. 6–2(a). An equal but oppositely directed current sheet would then be induced within the plasma, starting initially near the walls, but driven rapidly inward toward the center as a result of the buildup of the longitudinal magnetic field in the annular region. By comparison with this analogous situation in the pinch, shown in Fig. 6–2(b), it is seen that the current and field configurations of the two systems are similar, but orthogonal (perpendicular) to each other.

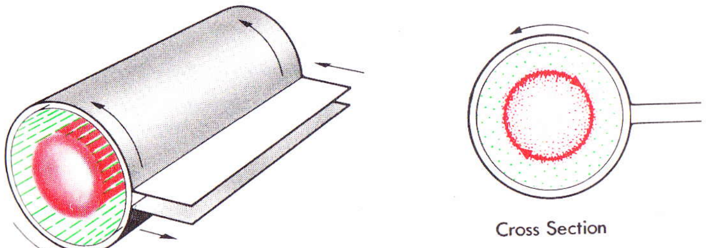
Here, however, the similarity ends. In the pinch configuration the magnetic field driving the plasma particles toward the center increases in strength as they move inward, whereas in the inverse configuration the magnetic field responsible for the inward force drops off as the plasma particles move toward the center. The buildup of plasma pressure in the interior of the discharge sheet as a result of its compression and heating by the shock causes the inward-moving plasma to come to a halt and to oscillate about some intermediate radius, randomizing its translational energy and thereby increasing the temperature of the plasma still further.

In preliminary investigations of this latter shock-heating process (to which Colgate gave the name "Collapse"), the rapidly rising magnetic field was applied to a cold, un-ionized gas. It was found, however, that the rate of ionization by the induced electric field was too slow to permit the formation of a clearly defined shock front.

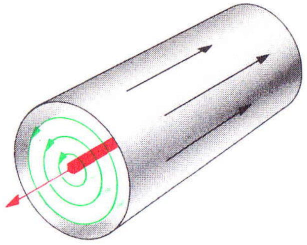
To overcome this difficulty, work was begun on a modified experiment with provisions for pre-ionizing the gas and forming a sharp boundary layer prior to applying the final shock itself. The results of this work are discussed in Chapter 15.

AT TUFTS COLLEGE, MEDFORD

At Tufts College, Medford, Massachusetts, a small group working under contract with the Air Force had been studying the properties of flow discharges in the presence of magnetic fields. Early in 1952, this group became interested in the pinch effect and carried out small



(a) Configuration in "Collapse"



(b) Pinch Configuration

FIG. 6–2. COLLAPSE CONFIGURATION VS. PINCH CONFIGURATION. (a) The sudden discharge of a current in the metal conductor encircling the discharge tube produces an oppositely directed current sheet in the plasma. In the annulus between these current sheets, an axial magnetic field is produced, which drives the plasma inward, shock-heating it in the process. The collapse configuration is seen to be "orthogonal" to the pinch configuration shown in (b); i.e., the positions of the current and the magnetic field lines are interchanged.

scale experiments involving this approach over a period of several years. While this work was never a part of the AEC program, several of the staff (W. H. Bostick and M. A. Levine) attended the AEC Sherwood conferences and made a number of valuable contributions. In 1954, Bostick joined the staff of UCRL, Livermore, to work on linear pinches; shortly afterwards, Levine transferred to the Cambridge Air Force Research Laboratory, where he continued much of his earlier work under the direction of M. O'Day.

At New York University

Because of the complexity of some of the theoretical problems which were being faced in the Sherwood field, it was felt desirable to obtain the assistance of some of the staff of the Institute of Mathematical Sciences at New York University (NYU). This Institute, under the direction of R. Courant, was particularly qualified in the closely related field of gas dynamics, shock waves, and electrodynamics.

At the instigation of the Division of Research, a small theoretical program in the Sherwood field was started at NYU in the spring of 1954. Under the direction of H. Grad, a wide variety of theoretical problems was studied, with emphasis on the application of known methods in gas dynamics to the field of magneto-hydrodynamics (the behavior of a plasma in a magnetic field).

Over the ensuing years, a number of important contributions were made on subjects of interest to the Sherwood program. Several aspects of this work will be discussed in Chapter 14.

Additional Developments

It is appropriate to mention here several additional developments that made their appearance before the end of 1954. Some of these are discussed in more detail in later chapters.

At the Berkeley Sherwood Conference in April, 1953, M. L. Good of UCRL proposed a scheme for the containment of a hot plasma by means of radiofrequency electromagnetic fields in a resonant cavity. After rather detailed theoretical consideration of this proposal, however, it was generally concluded that the particle density and temperature that could be achieved in this way would not be adequate for Sherwood purposes.

In February, 1953, a wholly new concept for a controlled thermonuclear device was disclosed to the Commission by N. C. Christofilos, a U. S. citizen who had lived most of his life in Greece and had just returned to the United States. Shortly before his return, Christofilos had worked out by himself the general principles of his thermonuclear concept.

This proposal was carefully reviewed and evaluated. Because of its potential importance, Christofilos was invited to present his views in a special session held at the end of the classified Sherwood conference on April 7, 1953. The general conclusion was that, while ingenious, the concept forwarded by Christofilos was complex and crude in its original form. Serious doubt was cast on the feasibility of certain of its features, and it was suggested that Christofilos should analyze these topics further.

Upon accepting a position at Brookhaven in 1953 to work on other matters, Christofilos continued to spend part of his time on modifying and improving his concept in an effort to overcome the objections which had been raised. Further discussion of his approach, which later received AEC support, is given in Chapter 16.

Still another concept for a controlled thermonuclear device was proposed to the AEC in July, 1953, by R. R. Wilson of Cornell University. Simply described, it involved heating the plasma by means of a converging electrodynamic wave in the presence of an increasing magnetic field. This proposal, which was explored experimentally by J. W. Mather at Los Alamos, using an apparatus known as Jug, produced a short-lived flurry of activity and optimism. While it was subsequently judged to be of limited interest in its original form, it provided the basis for much of the later work on shock heating of a plasma.

In September, 1953, the California Research and Development Corporation, which had been working under AEC contract on the development of a large accelerator at the Livermore Laboratory and was familiar with the work on Sherwood magnetic mirror activities there, proposed the initiation of a research and development project involving the injection of a high-energy deuteron ion beam into a relatively low-energy plasma confined by magnetic mirrors. It was finally decided, however, that this proposal did not constitute a sufficiently different approach to warrant starting a separate project at that time.

During 1954, W. H. Bennett, of the Naval Research Laboratory (NRL), submitted to the AEC a novel proposal for producing thermonuclear reactions. He proposed creating, by means of a special accelerator known as a "polytron," a self-focusing stream of high-energy ions, neutralized by low-energy electrons. The relative energies of the ions in the beam would be sufficient to produce thermonuclear reactions. While apparently correct in principle, this concept was not pursued, since it was judged that in practice the ion currents could not be made sufficiently large for practical Sherwood purposes.

A small research project on shock waves was begun at Brigham Young University (Utah) under the direction of R. Hales. This effort was a continuation of work which Hales had undertaken earlier at Livermore, in connection with the magnetic mirror program.

Several other laboratories (e.g., the Naval Research Laboratory and Massachusetts Institute of Technology) expressed interest in the Sherwood program, and the Commission took steps to encourage their participation.

CHAPTER 7

THE COORDINATION AND ADMINISTRATION OF THE SHERWOOD PROGRAM (PART I)

1951 TO END OF 1954

As pointed out in the preceding chapters, the major programs in controlled fusion sprang up more or less spontaneously at three different laboratories about the country. Partly for historical reasons, the responsibility for each of these three Sherwood projects automatically fell under a different division of the Atomic Energy Commission: that at Los Alamos was the responsibility of the Division of Military Application; that at Livermore fell under the Division of Reactor Development, which at that time had responsibility for much of the work at UCRL; and that at Princeton was under the Division of Research.

Because of the research nature of the effort, however, the Commission requested T. H. Johnson, Director of the Division of Research, to take the initiative for directing and administering the Sherwood program as a whole. In this function, it was his responsibility to keep the Commission informed of the technical progress of the program; to advise in such matters as its program, its scope, its staffing, its financing; to recommend levels of effort; to stimulate new interest and activity; and to undertake many other matters. Several of these topics are discussed briefly below.

SHERWOOD CONFERENCES

One of the immediate requirements in the early days of the Sherwood effort was to attract additional qualified people to participate in the program and to stimulate the flow of new ideas. Both for this purpose and also to assure adequate interchange of information among the various projects, Johnson inaugurated a series of classified conferences in the controlled thermonuclear field.

The first conference of this type, dedicated to a discussion of the problems involved, the approaches under way, and the outlook for eventual success, was held at the University of Denver on June 28, 1952. In the hope of encouraging work at other AEC sites, representatives were invited from most of the major laboratories, and the meeting was attended by more than eighty scientists.

A similar but slightly smaller meeting was held some nine months later, on April 7, 1953, in Berkeley, California. Following presentation of the technical papers, a round-table discussion was held on the present status and future hopes of the Sherwood effort. The participants were E. Teller, L. Spitzer, Jr., E. McMillan, R. F. Post, J. L. Tuck, and M. H. Johnson. While there was a healthy divergence of views concerning the optimum method of producing thermonuclear reactions, on one point there was universal agreement: that there appeared to be no fundamental reason why such a goal should not eventually be achieved.

These conferences* and those which followed proved fruitful in every respect. Besides surveying the technical progress of the major programs, they provided a welcome opportunity for discussing new ideas and presenting work in related fields.

The Question of Appropriate Classification

From the very beginning of the Sherwood effort, the question arose as to the security classification which should appropriately be applied to this work. On the one hand, it was well recognized that success in the controlled thermonuclear field would provide a new and copious source of neutrons—neutrons which could then be used, if one chose, to produce special material, such as plutonium, having great military value. At that time, in 1952, neutrons were a scarce and expensive commodity, capable of being produced in quantity in only a very few countries. It was thus clear that the quick realization of a controlled thermonuclear device would have appreciable military significance. This fact alone constituted strong justification for carrying out the work on a classified basis.

On the other hand, it was also recognized that the work was in the very early stages of research and that in all probability a great many years of intensive effort would be required before a full-scale thermonuclear device could be successfully developed. Over a time scale of this magnitude, the military importance of such a device could be expected to decrease considerably. It was also clear that the work would necessarily proceed at a somewhat slower pace if it were carried out on a classified basis. Recruiting qualified people, for example, would become much more difficult, particularly in the case of Princeton, which had very few staff members already cleared for work on classified projects.

Cogent arguments could thus be advanced both for and against the desirability of carrying out the Sherwood work on a classified basis, and the matter was deliberated at great length in the laboratories, at the Sherwood meetings, and throughout the Commission. The advice of many people was sought and many widely divergent views were expressed. After considering all aspects of the matter, the Commission finally decided that the work should continue on a classified basis for the time being, pending a better determination of the problems involved and the difficulty of achieving success.

The Magnitude and Coordination of the Effort

There was, however, strong interest on the part of the Commission, and particularly its chairman, L. L. Strauss, to ensure that the program move ahead with all possible speed and that it not be hampered by problems of organization or finance. To this end, a meeting was convened in Washington on September 21, 1953, for the express purpose of determining, in the light of the progress made to date and the outlook for success, how rapidly the program should be pushed

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* The major Sherwood Conferences were the following:

Date	*Location*
June 28, 1952	Denver, Colorado
April 7, 1953	Berkeley, California
June 24, 1954	Los Alamos, New Mexico
October 26–27, 1954	Princeton, New Jersey
February 7–9, 1955	Livermore, California
June 10–11, 1955	Los Alamos, New Mexico
October 17–20, 1955	Princeton, New Jersey
June 4–7, 1956	Gatlinburg, Tennessee
February 20–23, 1957	Berkeley, California
October 17–18, 1957	Princeton, New Jersey
February 3–6, 1958	Washington, D. C.

and how big a gamble could appropriately be taken at this stage. In addition to the Commission staff, the following were present: E. O. Lawrence, J. Von Neumann, R. F. Post, I. I. Rabi, L. Spitzer, Jr., E. Teller, J. L. Tuck, and R. R. Wilson.

Among the conclusions of this meeting, it was generally agreed:

(a) that the Sherwood effort should be considered as a long-range proposition and that it was idle at this stage to speculate on the economics of full-scale thermonuclear reactors,

(b) that the field might well prove to be extremely important—perhaps the most significant of all the AEC activities—and that a more intensive developmental effort was surely justified,

(c) that while additional basic research was required before the projects could be profitably expanded to any appreciable degree, it was likely that a number of heavy engineering projects could appropriately be undertaken during the following year, and

(d) that in preparing for a rapidly expanding effort, it would be advantageous to increase the coordination of the over-all program and establish still closer working relationships among the laboratories engaged in the work.

In accordance with these views, a number of organizational changes were instituted within the Commission during the next several months. As mentioned earlier in this chapter, the spontaneous development of the various Sherwood projects had resulted in diversified administration of their activities under three separate divisions of the AEC. Steps were now taken to centralize completely the direction, coordination, and administration of the entire Sherwood program under the Director of Research, T. H. Johnson. In turn, Johnson delegated the responsibility for handling these matters to A. S. Bishop of his staff.

To ensure still greater unification and coordination of the work in the major projects, Johnson established a Sherwood Steering Committee, composed of E. Teller as chairman, W. Brobeck, L. Spitzer, Jr., and J. L. Tuck, with A. S. Bishop as executive aide. The purpose of this advisory committee was to assist the Division of Research in such matters as evaluating the progress made and the program proposed, suggesting what new research projects should be undertaken and by whom they might best be carried out, and recommending appropriate levels of activity. From its inception in January, 1954, the Committee met fairly regularly at four-month intervals.

Steps were also taken to intensify the Sherwood effort as soon as possible. Plans were drawn up with the project directors to move ahead at more than twice the pace originally contemplated, with provisions for still further increases if the results were exceptionally promising.

CHAPTER 8

PLASMA DIAGNOSTICS

In previous chapters we have discussed the beginnings of several different approaches to the problem of confining and heating a plasma. Before taking up the next phase of the work, let us diverge for a moment and consider a topic essential to the progress of all approaches. This is the matter of determining, or "diagnosing," exactly what is happening in the experiments being performed.

One must, for example, be able to answer such questions as: What temperatures are being achieved? What is the density of the ions? How long does the plasma remain confined? What impurities are present and to what extent? This is the so-called field of "plasma diagnostics," in which the investigator determines the characteristics and behavior of the plasma. Several of the more important techniques developed for this purpose are briefly described below.

Photography

One of the more valuable techniques is that of photographing the plasma within the discharge tube. Since the discharge usually lasts just a fraction of a millisecond, high-speed photography is required. Two types of equipment have been used with marked success:

(a) "Streak" (or "smear") cameras which incorporate a rapidly rotating mirror. Light from a narrow section of the discharge tube is focused onto the mirror, from which it is reflected to a strip of film in the form of an arc (see Fig. 8–1a). The rapid rotation of the mirror sweeps the light over the film and, by properly synchronizing the shutter, one may obtain a continuous record of the behavior of the discharge over the brief period of interest. Using this technique, it was possible, for example, to obtain clear evidence of the instability of the pinched discharge. The formation of the pinch and subsequent development of the kink instability would appear roughly as shown in Fig. 8–1(b).

(b) "Image converter" cameras, with which it is possible to obtain an image of the discharge covering a period as short as a mil-

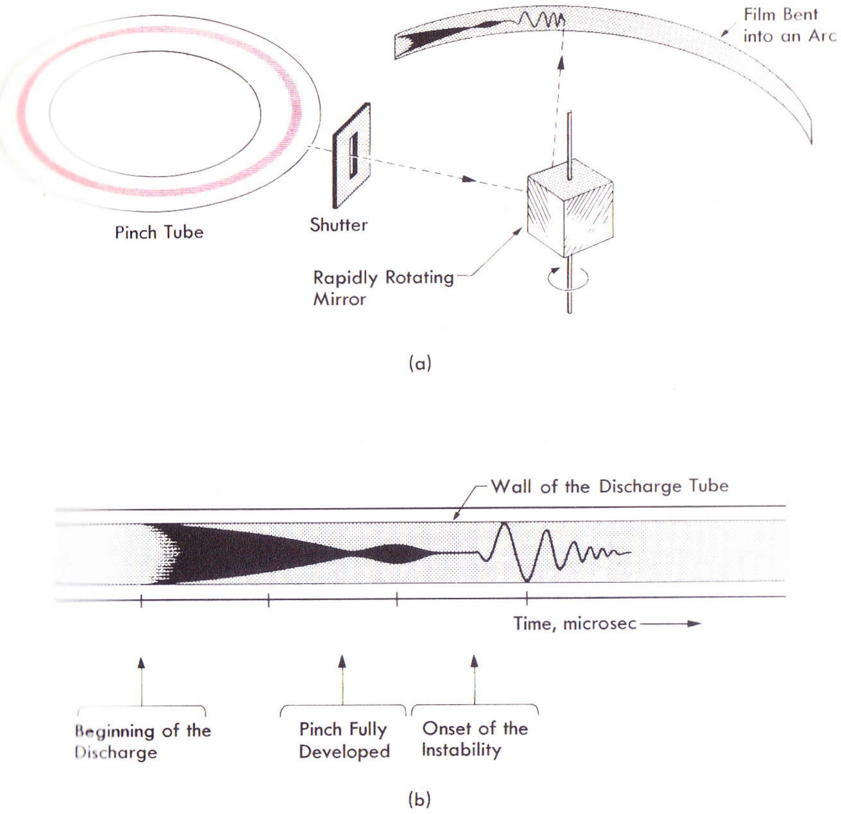


FIG. 8–1. STREAK CAMERA. (a) Light from the plasma discharge is reflected from a rapidly rotating mirror onto a strip of film. (b) Sketch of a photograph from a streak camera, showing the formation and breakup of a pinch discharge.

lionth of a second. With this camera, which uses electronic amplification, one may select at will the exact instant at which the photograph is to be made. Hence, by taking a sequence of pictures of discharges at successively delayed intervals, it is possible to obtain a detailed record of the behavior of the plasma.

Spectroscopy

A more important means of plasma diagnostics is by spectrographic analysis of the light emitted in the discharge. Without going into details here, suffice it to say that this type of analysis can provide detailed information concerning such matters as (a) the composition and the degree of purity of the plasma, (b) the electron temperature (by measuring, for example, the relative intensities of certain spectral lines or the rate at which electron collisions ionize atoms), and (c) the ion temperature (by measuring the "Doppler broadening" of individual spectral lines, resulting from the motion of the ions themselves).

Both photography and spectroscopy are extremely useful diagnostic tools in the early stages of research and development, that is, for plasma temperatures up to several million degrees. For higher temperatures, however, any plasma of high purity is essentially completely ionized and thus, strange as it may seem, emits relatively little visible light. Optical methods of analysis are then of limited usefulness, and other techniques become increasingly important.

Microwave interactions

Another powerful technique is to probe the plasma with a beam of high-frequency electromagnetic radiation (microwaves). By measuring the phase shift, absorption, and scattering of microwave radiation propagated through the plasma region, valuable information can be gained concerning the electron density therein. In addition, electron temperatures may be deduced from microwave "noise" emitted from the plasma.

Magnetic probes

In many experiments, it is desirable to know the strength of the magnetic confining field at one point or another within the discharge tube. A knowledge of this field strength can yield valuable information concerning the effectiveness of plasma confinement; it may, in some cases, even permit plasma temperatures to be deduced. (See Chapter 10.)

One of the more important techniques is the use of magnetic probes, consisting of tiny coils of wire about a millimeter in diameter, embedded in the ends of small quartz tubes. Such tubes may be pushed in to any desired region of the discharge chamber; voltages induced in the probe coils then give a measure of the rate of change of field strength at that point.

While probes are extremely useful in many experiments, there are several limitations to their use. One difficulty is that they introduce impurities as a result of partial evaporation of their walls by the discharge. Another is the fact that, tiny as they are, they nevertheless tend to perturb the discharge locally; as a result, the accuracy of the information they yield may be subject to question.

Neutron emission

Certainly one of the more satisfying methods of plasma diagnostics would be by measurement of neutrons emitted from thermonuclear reactions in the plasma itself. As pointed out in Chapter 1, the rate of fusion reactions between deuterons increases very rapidly with temperature up to about 100,000,000°K. Below a million degrees or so, the number of neutrons emitted would be too few to be detectable. Between these two limits, however, neutron emission can provide a sensitive method of measuring plasma temperatures. In addition, it can yield information on plasma density and position.

There are a number of different ways of detecting the emitted neutrons. One of the more common methods is to use photographic emulsions and look for the tracks left in the emulsion by the recoil of nuclei that have been struck by the neutrons. Another is to use scintillation counters, which detect neutrons by the flashes of light emitted as a result of knock-on collisions in the scintillator material.

A word of caution is appropriate, however, concerning the use of neutrons as a diagnostic tool. Care must be taken to ensure that the neutrons really originate from fusion reactions within the plasma itself and not from other spurious processes of relatively little interest. As will be seen in later chapters, the distinction is often difficult to make, and initial interpretations may be misleading.

Other methods

In addition to those described briefly above, many other diagnostic techniques have been developed and found useful in the Sherwood field. Electron energies can, for example, be determined from x-ray measurements. Changes in size, shape, or position of plasma body can be inferred from the measurement of voltages and currents induced in external circuits. Escape rates of ions and electrons from the confinement region can be deduced from Faraday cups and other charged-particle collectors.

Rapid strides have been made in the field of plasma diagnostics during the past few years. Early techniques have been improved and new ones developed. While each has a limited range of accuracy or usefulness, the knowledge gained from one method tends to complement or extend that gained from another. In this way, slow but steady progress is being made toward accurate diagnosis of plasma behavior over a wide variety of operating conditions.

CHAPTER 9

THE QUESTION OF STABILITY

Growing concern

During the early days of the Sherwood program, the degree of understanding concerning the behavior of a plasma in electric and magnetic fields was exceedingly small. Simply to compute the behavior of *individual* particles in these fields was sufficiently complicated; the problem of determining the joint motion of a group of particles, taking into account all their interactions, was much more complex.

As a result, relatively little thought had been given to the general problem of stability and the criteria for achieving a stable system. Calculations had, in fact, been carried out for only one specific case of interest in the Sherwood field, that of the simple pinch (see Chapter 3). The results of these calculations had certainly given no grounds whatsoever for complacency; the configuration had been found to be unquestionably and inherently unstable.

While there was little discussion of the matter because of its complexity, there was growing concern, particularly on the part of E. Teller, that the stellarator and magnetic mirror configurations might also be subject to instabilities.

Teller's criterion for stability

The matter came to a head in October, 1954, at a Sherwood conference held at Princeton. It was then that Teller finally gave voice to his concern over this matter and suggested on intuitive grounds a simple criterion for determining the stability of a plasma confined by a magnetic field.

Teller pointed out that, figuratively speaking, magnetic lines of force tend to act like rubber bands, contracting and shortening themselves wherever possible. The plasma, on the other hand, behaves like a gas under pressure seeking to expand to larger volumes. One might therefore expect that any configuration of the type shown in Fig. 9-1(a), in which the magnetic field lines bend concavely toward the plasma, would be unstable, since the magnetic field and plasma would tend to interchange positions. The magnetic field lines would seek to shorten themselves by moving into the region initially occupied by the plasma; the plasma, in turn, would seek to expand into the region initially occupied by the magnetic field. Conversely, a configuration similar to that shown in Fig. 9–1(b) would be expected to be stable, since here the magnetic field lines bend convexly away from the plasma and do not seek to interchange position with it. The intermediate case, shown in Fig. 9–1(c), could then be said to have neutral stability.

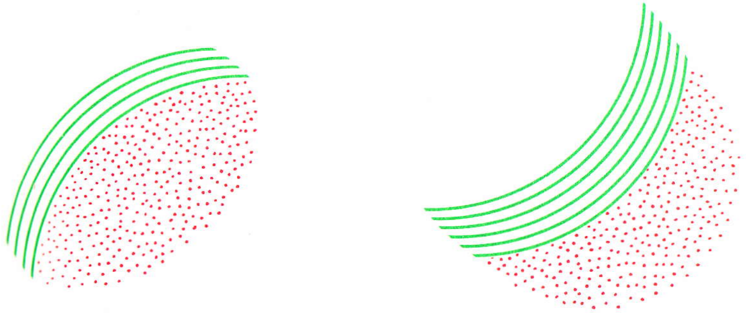
Teller's suggestion caused grave concern at the conference, for (if valid) it implied that in addition to the known (kink-type) instability of the pinch geometry, the stellarator and the magnetic mirror configurations should also be unstable. In both of these latter approaches there were regions where the magnetic field lines bent concavely toward the plasma and "interchange instabilities" would hence be expected to develop.

Much discussion was aroused, and the experimental data available at that time were reviewed for evidence in support of, or conflicting with, the view advanced by Teller. Unfortunately, the data were too meager for any conclusions to be drawn one way or the other. Moreover, it was pointed out that in the experimental work performed up to that time the plasma pressure had always been small in comparison with what the magnetic field was capable of exerting. It seemed reasonable to believe that interchange instabilities, if they were to occur at all, might arise only when these two pressures approached comparable size. To put it another way, it appeared logical that instabilities would be more likely to appear under conditions of high β than under the very low β conditions which had been realized in the experimental models to date.

Picket-fence concept

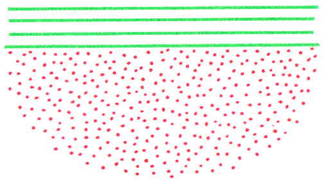
With doubt cast on the stability of all the approaches being pursued, the question arose as to whether, under the criterion tentatively proposed by Teller, it was possible to devise any method of plasma confinement which would be inherently stable. In answer to this question, Tuck proposed a concept which he had formulated at Los Alamos in connection with another matter.

In this concept, to which the name of "Picket Fence" was given,



(a) Unstable Configuration

(b) Stable Configuration



(c) Configuration with Neutral Stability

Fig. 9–1. Criteria of Stability. In (a) the magnetic field lines tend to bend inward, interchanging position with the plasma. In (b) the field lines bend away from the plasma and there is no tendency for interchange of position. The intermediate state (c) may be said to have neutral stability.

current is passed through an array of conductors to produce a magnetic field configuration shown schematically in Fig. 9–2. Here, the lines of magnetic force everywhere bend *convexly* from the plasma, thereby satisfying the Teller requirements for stability. With a configuration of this type, one could envisage numerous ways in which the plasma could be enclosed and confined.

The suggestion of the picket-fence concept did little, however, to dispel the atmosphere of gloom which settled over the conference toward its end. The stability criterion which had been suggested by Teller was admittedly tentative, but it seemed dismayingly reasonable; perhaps more important, it brought the whole of the Sherwood program face to face with a problem which threatened its very existence.

Subsequent confirmation

In the next several months, the attention of theorists and experimentalists alike was turned toward study of the difficult and complex problem of stability. For a time, all that could be obtained were incomplete or too-limited theoretical treatments of the problem. Then, independently, three different and incontrovertible proofs of the correctness of these criteria appeared, as a result of the independent work of E. A. Frieman at Princeton, H. Grad at N.Y.U., and C. L. Longmire at Los Alamos. In particular, Frieman's treatment was for a configuration of magnetic field lines approximating those occurring in the stellarator and magnetic mirror machines. Under the assumptions made, the results gave clear evidence of instability; moreover, they predicted that the instability should occur for *all* values of β, rather than simply for high values.

These results, reported at a Sherwood conference in Berkeley in February, 1955, were confirmed and extended by a team of theoretical physicists working at Los Alamos during the summer of 1955. This group, which included C. L. Longmire, M. N. Rosenbluth, M. L. Goldberger, and K. M. Watson, analyzed the problem in a number of different ways. While the cases considered theoretically were admittedly only an approximation of the more complex experimental conditions, the weight of evidence pointed ominously in the direction of instability for both the mirror machine and the stellarator.

The impact of these theoretical results on each of the experimental programs is discussed in the following chapters.

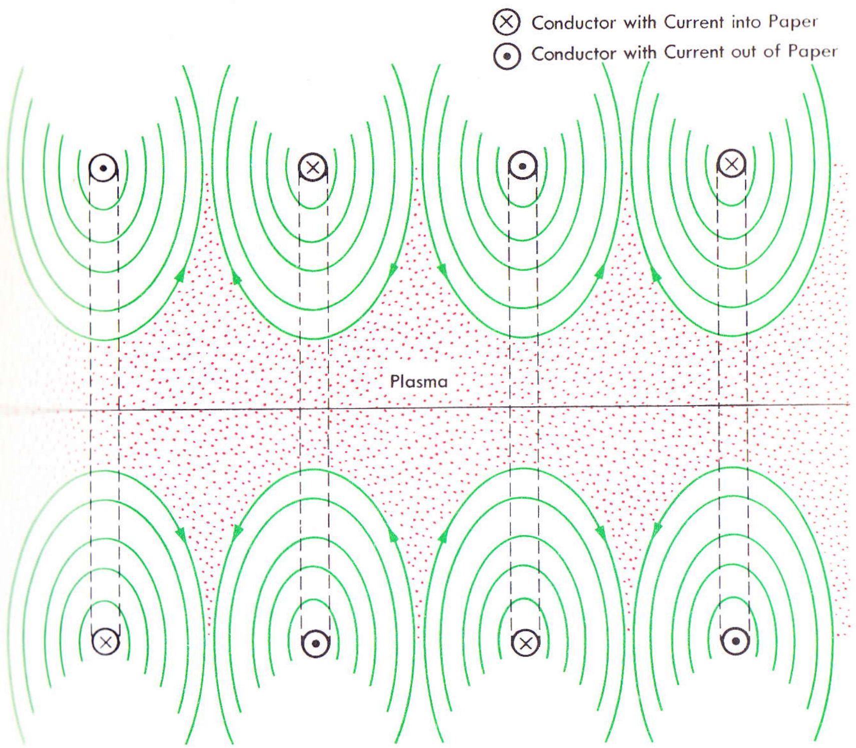

⊗ Conductor with Current into Paper
⊙ Conductor with Current out of Paper
Plasma

Fig. 9–2. Picket-Fence Concept. Current-carrying coils are so arranged that the resulting magnetic field lines bend convexly away from the plasma at all points, thus giving a stable configuration.

CHAPTER 10

THE PINCH PROGRAM (PART II)

A. From 1955 to Mid-1956

Of all the Sherwood projects, the pinch program was probably the least affected by the recent concern over stability. From the very beginning, the pinch had been recognized to be unstable; now it appeared that other approaches might possibly join its ranks.

In any case, the alternatives were still much the same as before:

(a) If worse came to worst, and all existing programs appeared doomed by instabilities, there was always the possibility of turning to some configuration such as Picket Fence (page 86), which appeared to possess inherent stability. To do this, however, meant jettisoning the work already done and beginning again with a wholly different approach.

(b) A second alternative would be simply to give up all thought of stable operation and try instead to produce a very fast and powerful pinch, in the hope of achieving significant amounts of thermonuclear burning in the brief interval before the onset of instabilities. As mentioned earlier (pages 31–32), a practical reactor based on a "dynamic" pinch of this type appeared to require enormous equipment, from which energy would be released in the form of minor explosions!

(c) But best of all, of course, would be to find some method of stabilizing the pinch configuration. This possibility was unquestionably intriguing; the only difficulty was that no one knew how to do it.

Needless to say, the outlook was not altogether cheerful; but neither was it any worse than it had been before. In the absence of any obvious advantage of one alternative over the others, all three were investigated more or less seriously. A summary of these investigations is presented below.

Picket Fence

The picket fence concept was examined in some detail by a small group at Los Alamos, with additional theoretical assistance from H. Snyder at Brookhaven. Analysis showed, however, that while this method of plasma confinement apparently offered the valuable feature of stability, it suffered a severe disadvantage of another nature: it was "leaky." Individual particles moving in the magnetic field associated with the picket fence configuration would tend to squeeze out through the small openings between the lines of force long before they would be likely to undergo fusion with one another. Various methods were proposed to decrease this loss, but none gave any hope of success. Because of the increasingly favorable outlook for other approaches, further work on Picket Fence was eventually shelved at Los Alamos. However, an interesting and promising modification of this concept was studied in detail by a group at New York University (see Chapter 14).

Fast pinch; origin of neutrons

Meanwhile, intensive work was underway—both by Tuck's group at Los Alamos and, more recently, by a group under W. Baker at UCRL, Berkeley—to exploit the concept of the fast pinch. As pointed out earlier (pages 28–31), the theoretical results of Rosenbluth indicated that high voltage gradients were required to produce a fast pinch and the high associated temperatures. To facilitate achieving such gradients, experiments were carried out with linear discharge tubes, and special care was taken to minimize the inductance of the system as a whole.

Early in 1955, shortly after the experimental models* were put into operation, neutrons were detected nearly simultaneously by the groups at both laboratories. They appeared sporadically at first and in a wholly unreproducible manner. On one discharge, there might be as many as 10^5 neutrons; on the next attempt, with apparently identical operating conditions, the number might drop by a factor of fifty or more.

However, as the result of a series of improvements, many of them empirical in nature, the production of neutrons became increasingly consistent, and it was possible to undertake meaningful experiments to determine their origin and nature. The big question was whether or not the neutrons were really of thermonuclear origin. Said another way, the question was (a) whether the neutrons originated within the discharge itself as a result of the fusion of uniformly hot deuterium plasma in random thermal motion, or (b) whether they had been produced by relatively few plasma ions which had somehow been accelerated unidirectionally to high energies (the rest of the plasma remaining relatively cold), and which were striking other deuterium ions adsorbed, say, on the electrodes or walls of the discharge chamber. The first process would be of real interest, the second of trivial value.

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* Called "Columbus I" at Los Alamos and "Linear dynamic pinch" at Berkeley.

The series of elaborate experiments, carried out at both laboratories with direction-sensitive neutron counters and nuclear emulsions, showed conclusively that the neutrons were coming from neither the electrodes nor the walls of the discharge tube. Instead, they were orginating within the interior of the plasma discharge itself. In another set of experiments, it was found that the neutrons were still observed when the voltage applied to the discharge tube was reduced to 10 kilovolts or less, provided that compensations were made to ensure (in accordance with the requirements of the theory) the same velocity of inward motion of the magnetic wall. From these results, it seemed clear that the neutrons were not being produced by high-energy deuterons impinging upon the walls or electrodes of the discharge tube. Hope ran high that they were of true thermonuclear origin.

This hope was short-lived, however. Two bits of evidence were accumulated that could not be reconciled with the theory of thermonuclear origin. In the first place, the number of neutrons observed was too great; under the operating conditions of the experiments, the temperatures predicted from the Rosenbluth theory were too low to produce so many neutrons from fusion reactions. The second and even more convincing evidence was the result of a careful study of the energy spectrum of the neutrons which were emitted. This study, carried out initially at UCRL, Berkeley, showed that while the neutrons were coming from the body of the discharge, the deuterons responsible for their production (through the D-D reaction) were unquestionably moving with rather high velocities in the *axial* direction. The deuterons, therefore, did not have random velocities, as required for true thermonuclear conditions. Instead, they had somehow acquired axial velocities greater than they could have achieved by being accelerated the entire length of the tube!*

This was a real paradox, and numerous proposals were advanced to explain it. Perhaps the most widely accepted explanation was that proposed by S. A. Colgate early in 1956. He concluded that the neutron production was associated with the onset of the pinch instability. More specifically, he showed that in the development of the "sausage-type" instability (see Fig. 10–1), very large axial voltages could develop across the pinched-off regions—voltages several times higher than that applied across the tube itself. Under the influence of such voltages, a small fraction of the plasma ions would be given high velocities along the axis of the tube and would collide with other (cooler) plasma particles in the main body of the pinch. It was easily possible, on the basis of this proposal, to account for the large number of neutrons observed.

Since the plasma as a whole had not been raised to thermonuclear temperatures, the neutrons produced in this process were clearly of *non*thermonuclear origin, and were given the name of "instability neutrons" (or "false neutrons"). The study of these spurious particles provided an interesting diversion; it was recognized, however, that the immediate goal was to increase the temperature of the plasma as a whole before the onset of any instabilities. Then and only then could "real" or thermonuclear neutrons be expected.

One immediate difficulty appeared to stand in the way of achieving this goal. For satisfactory operating conditions, it was essential for the gas to be fully ionized before the pinch voltage was applied. Otherwise the later ionization of gas left behind near the walls would tend to slow the inward motion of the pinch and prevent the achievement of high plasma temperatures. It was thus necessary to develop a satisfactory method of "preheating" the gas before applying the pinch voltage. At Los Alamos, work was begun on the second model in the Columbus series, a powerful device known as Columbus II, in which provisions were made for plasma preheating.

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* For example, with only 20 kv applied across the tube, the deuterons responsible for producing the neutrons were found to have an average energy of the order of 50 kev.

Stabilization of the pinch

Meanwhile, the outlook for stabilizing the pinch took a sudden turn for the better. Largely as a result of the efforts of Colgate, the question was raised again as to whether complete stabilization might not be achieved by a suitable combination of (a) an axial magnetic field in the interior of the pinch to stabilize the sharp (short wavelength) kinks, and (b) conducting walls around the discharge tube to stabilize the broad (long wavelength) kinks. A drawing of such a configuration is shown in Fig. 10–2.

This approach had been considered earlier (see pages 28–29), but in the specific cases analyzed at that time, it had not been found possible to achieve adequate stability. Toward the end of 1955, however, M. N. Rosenbluth (LASL) made a more general mathematical treatment of the problem and found that the above combination should, in fact, provide complete stabilization of the pinch if certain specific conditions were met. Among the more important of these conditions were (1) that the radius of the fully formed pinch not be any smaller than one-fifth the radius of the discharge tube, and (2) that there be a sharp boundary between the region containing the axial magnetic field (and hot plasma) and that containing the encircling (azimuthal) field outside.

B. Mid-1956 to 1958

Experimental confirmation of stabilization

The above possibility of pinch stabilization constituted a major landmark in the pinch program and stimulated a surge of experimental activity at both Los Alamos and UCRL. Numerous models were put into operation over the following two-year period in an effort to confirm the predictions of the theory, or at least to determine its limitations. Several of the more important experiments are indicated in the chart of the Pinch Program in Appendix X.

To gain experience as quickly as possible, much of the equipment previously used in the fast pinch work was modified to permit studies of stabilization. As a result, the first experiments on stabilization used linear discharge tubes (of quartz or some other insulating material), surrounded with closely fitting conducting walls and encircled

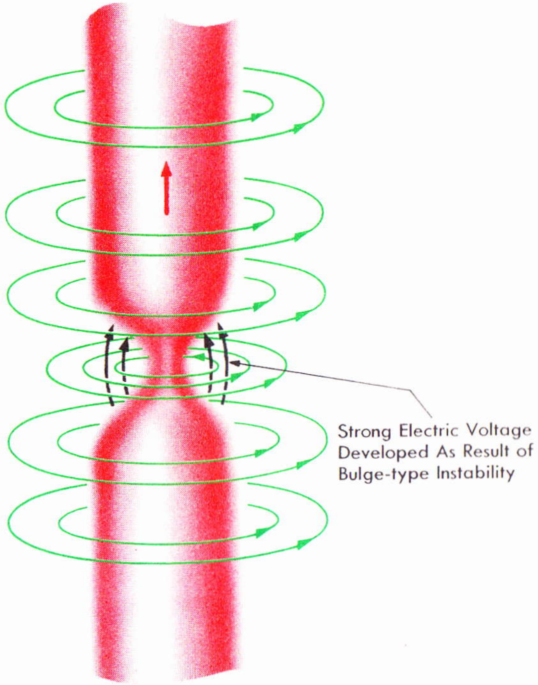

Strong Electric Voltage Developed As Result of Bulge-type Instability

Fig. 10–1. Proposed Origin of Instability Neutrons. Instability neutrons may be produced as a result of deuterons accelerated axially by voltage induced through the onset of a "sausage-type" instability.

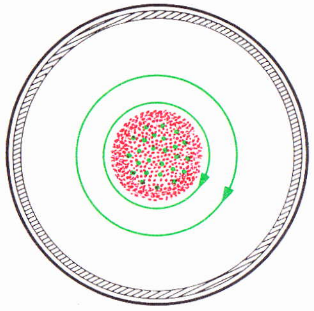
with current-carrying coils to provide the necessary axial stabilizing field. It was of course recognized that if the pinch could be effectively stabilized, it would be essential to shift later to torodial configurations to avoid the cooling effect of electrodes.

Experiments carried out during 1956 with the small linear tubes were indeed rewarding. Measurements by a variety of methods showed conclusively that the pinch could be made to last for significant periods of time prior to breakup—periods five to ten times longer than had been previously possible. Another encouraging result was that, in accordance with theoretical predictions, the stability could be altered by modifying the amount of axial magnetic field external to the pinch. Detailed studies were begun to determine experimentally the exact conditions for stability and the reasons for final breakup.

Period of stabilization; interdiffusion of fields

One problem of immediate interest was to determine how long the pinch might be expected to stay stable. Clearly, it would not last *ad infinitum*. The axial stabilizing field would be expected to expand into, and mix with, the encircling magnetic field of the pinch. At some stage, then, the pinch would be expected to become unstable and break up. Thus the period of stability should be determined by the rate of intermixing, or interdiffusing, of the two fields. This rate should, in turn, depend on the plasma temperature. The higher the temperature, the lower would be the rate of intermixing, and hence the longer would be the time before pinch breakup. Theoretical studies showed that for full thermonuclear temperatures (100,000,000°K or more), this time should be very long indeed, many seconds for a pinch of moderate size. It could therefore be anticipated that if high temperatures could once be reached in a stabilized pinch, the discharge should remain stable long enough to allow extensive nuclear burning.

While on the one hand the interdiffusion of fields would have the detrimental effect of eventually destroying stability, there were compensating benefits which could be anticipated. As was pointed out by S. A. Colgate (and later analyzed in detail by M. N. Rosenbluth and A. N. Kaufman), the very process of interdiffusion of fields should itself result in substantial heating of the plasma. Simply



Cross Section

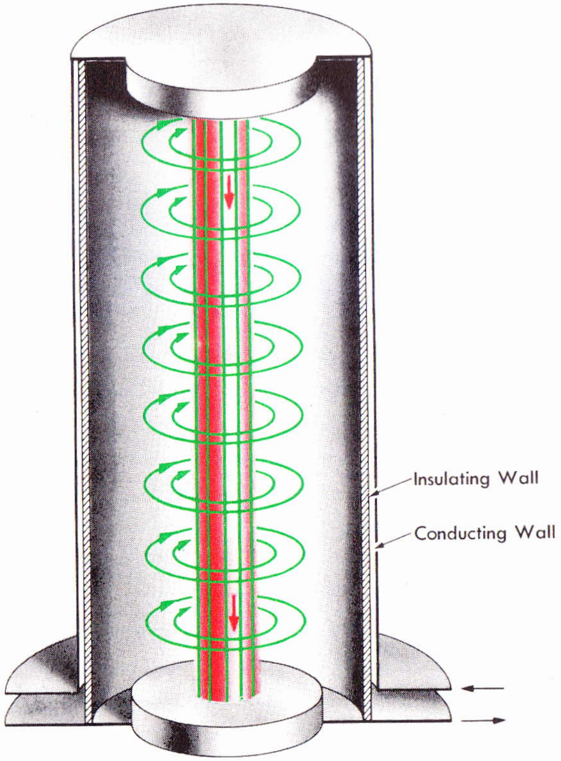


FIG. 10-2. THE B_Z STABILIZED PINCH. The presence of an axial magnetic field B_Z within the pinched plasma discharge provides a sort of "backbone" which tends to inhibit the development of kink and bulge-type instabilities. The combination of a B_Z field and external conduction walls should, under certain rigid conditions, permit complete stabilization of the pinch.

explained, as the axial magnetic field expands into the azimuthal field its energy content is diminished, and the energy of the plasma should be correspondingly increased. An important consequence of this fact is that before a stabilized pinch can break up, the plasma would necessarily be heated by the intermixing process. It was in fact shown that if the only energy loss were by the process of bremsstrahlung, then heating by interdiffusion should be sufficient to raise the temperature of the plasma to thermonuclear values.

Experimental verification by probe measurements

Experimental investigation of the above matters was facilitated at that stage by a powerful new diagnostic technique: the use of tiny magnetic probes. With probes of this type it was possible to measure the variation of axial and magnetic fields during the pinch discharge. Such measurements gave detailed insight concerning the formation of the plasma sheath, its contraction toward the center, the resulting increase in strength of the axial stabilizing field, the creation of a stabilized pinch (after several slight "bounces"), and then its breakup due to the eventual development of an instability. Of even greater interest, accurate knowledge of the fields made it possible to deduce the temperature of the pinched plasma by means of the so-called "pressure-balance" method.[*]

Using the probe technique, a series of experiments was undertaken at UCRL and Los Alamos to study the behavior of the stabilized pinch both in straight tubes and in toroids. Work at Livermore by S. A. Colgate, J. P. Ferguson, H. P. Furth, and others confirmed roughly the predicted relationship between interdiffusion of fields and plasma heating, and indicated the production of plasma temperatures in excess of 500,000°K. Measurements of a similar nature were carried out at Los Alamos by L. C. Burkhardt, R. H. Lovberg, J. A. Phillips, and others, using stabilized devices known as Perhapsatron S-3 and Columbus S-4. Temperatures of several million degrees were reported from their experiments, and sizable bursts of neutrons were detected during the time of the pinch. As of early 1958, the origin of these neutrons was not fully understood; they appeared, however, to be due to some sort of acceleration process within the plasma.

Problems associated with stabilization

The above developments were, on the whole, quite encouraging, and the pinch approach basked for several months in an unaccustomed glow of optimism. The optimism faded slowly, however, as a number of new and serious difficulties appeared. Several of these problems are described below, together with possible ways of alleviating them.

Problems of impurities from the walls. In the early days of the program, prior to the advent of stabilization, the process of pinch formation and breakup occurred so rapidly that there was no opportunity for impurities from the walls to enter and cool the discharge. With stabilization, however, the influx of impurities presented a major problem. To minimize this difficulty, two important modifications seemed essential: (a) increasing the bore of the discharge tube and operating with lower plasma densities; by so doing the intensity of heat transferred to the walls could be decreased and the impurities volatilized from them consequently reduced, and (b) lining the inside wall of the discharge tube with a low-Z material, thereby minimizing the cooling effect of whatever impurities still originated from this source.

Problem of producing sharp boundaries. In the original theory of Rosenbluth, one of the conditions of pinch stabilization was that there be a sharp interface between the axial stabilizing field and the circumferential field. That is to say, the field direction was assumed

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[*] The determination of temperature may be made as follows: the pinched plasma is confined by an inward pressure equal to $B_\theta^2/8\pi$. Under stable equilibrium conditions, this inward pressure is balanced by an equal and oppositely directed pressure made up of two components: that due to the stabilizing B_Z field ($= B_Z^2/8\pi$) and that due to the compressed particles of the plasma ($= nkT$). Thus, in the case of a sharp boundary between the axial and azimuthal fields at the edge of the current sheath, the following equation is valid at the boundary:

$$\frac{B_\theta^2}{8\pi} = \frac{B_Z^2}{8\pi} + nkT,$$

where the symbols have their usual significance (see Appendix VI). From the measured values of B_θ and B_Z and the estimated value of n, a determination may be made of the plasma temperature T. The above relationship is somewhat more complicated mathematically if the boundary is diffuse.

to change abruptly at the edge of the plasma. However, it was found experimentally that, for a variety of reasons, this assumption was far from being satisfied. Magnetic probe measurements showed that instead of being sharp, the interface was actually quite diffuse, even in the early stages of the pinch. While some improvement could be achieved by careful control over the axial magnetic field during the time of pinch formation (that is, by programming its magnitude and direction during this period), it was still not possible to achieve the desired sharpness.

Problem of achieving stabilization with diffuse boundaries. Concurrently with the above work, theoretical studies were carried out, particularly by B. R. Suydam and M. N. Rosenbluth, of the behavior of a pinched plasma with diffuse boundaries. Preliminary computations indicated that the stability conditions for the case of a diffuse boundary were even more severe than for a sharp interface. Among other conditions, it was found that, in contrast to the sharp boundary case, a reversed axial magnetic field external to the pinched plasma was now *essential* to stability. Moreover, the strength of this field had to fall within narrow, prescribed limits. There was also evidence that, quite apart from the major instability associated with eventual pinch breakup, there might also be interchange instabilities on the outer surface of the plasma. As of early 1958, the significance of such phenomena had not been fully analyzed.

Problem of heating to thermonuclear temperatures. One of the major difficulties was finding a satisfactory method of heating the plasma to thermonuclear temperatures. The powerful M-theory of shock heating, so useful in work on fast pinches (see page 29), was now of limited applicability. The presence of the axial stabilizing field slowed the inward motion of the shock and reduced its effectiveness in plasma heating.

The original pioneer heating process of inducing a low-gradient axial voltage in the discharge tube (a process discarded in the prestabilization days as much too slow and inefficient) still appeared to be unsuitable for achieving temperatures higher than several million degrees.

The process of heating as a result of the interdiffusion of crossed magnetic fields appeared to offer some promise. As already mentioned, calculations by M. N. Rosenbluth and A. N. Kaufman had shown that if the only mechanism of energy loss were bremsstrahlung, then the heating provided by crossed field interdiffusion should be sufficient to raise the plasma temperature from several million degrees on up to full thermonuclear values. The problem, however, was to find some way of creating a well-defined pinch at several million degrees, and to ensure that methods of energy loss other than bremsstrahlung do not occur.

In brief, no one method alone seemed adequate for heating the plasma. It appeared that a combination of these methods, supplemented perhaps by energetic particle injection, might ultimately be required to reach the desired temperatures.

Problem of spurious energy losses. The most ominous of all difficulties was the recent indication that large amounts of energy were being lost from the pinch discharge in spurious and unexpected ways. There was growing evidence, from measurement of plasma conductivity, that only a small fraction of the input energy was being retained by the plasma. By far the greater portion was apparently being rapidly transferred to the walls of the discharge tube by one mechanism or another—possibly as a result of runaway electrons escaping through the confining magnetic field. This matter will surely receive careful study in future experiments.

Status of the B_Z-stabilized pinch approach

The combined magnitude of the above difficulties has, naturally enough, led to some disenchantment with the stabilized pinch approach. It is to be hoped, however, that, as in the case of other difficulties in the past, these may be overcome in some way. It is, in fact, believed that proper conditions for stabilization in the presence of a diffuse boundary may well be achievable by accurately programming a reverse B_Z field during the process of pinch formation. The more immediate and difficult problem is to understand and learn how to combat the rapid rate of particle loss to the walls of the discharge tube.

While attempts were underway to solve the above difficulties, other approaches were not neglected. Active work still continued in the fast-pinch experiments, and several new methods of stabilization (or quasi-stabilization) made their appearance. A brief description of this work is given below.

Fast pinch experiments

Columbus II, a fast and powerful linear pinch experiment built at Los Alamos under the direction of J. W. Mather, went into operation in July, 1957 (Fig. 10–3). This model was designed with the goal of discharging large amounts of energy (100,000 joules) into the pinch tube in as short a time as possible. Great care had been taken to reduce the inductance of the system to a minimum, as a result of which it was possible to build up the current in the plasma to several million amperes in a microsecond or so. In addition, provisions had been made for "preheating" the plasma with a second and smaller power supply.

Under these conditions of operation, the number of neutrons increased by a factor of about 1000 over that initially achieved with Columbus I (i.e., to values of more than a hundred million per pulse).

Extensive measurements were carried out in an attempt to determine the mechanism of neutron production. These studies indicated that, once again, the deuterons responsible for neutron production were receiving a preferential acceleration in the axial direction by one means or another. A somewhat smaller but nevertheless marked "anisotropy" was found even if a small axial magnetic field were present within the pinched discharge, a field strong enough to inhibit the development of bulge-type instabilities but not enough to stabilize against other modes of pinch breakup (e.g., kink-type instabilities).

While there was some evidence that the neutrons were being produced by some mechanism other than the usual instability process, this question had not been fully resolved as of early 1958.

Screw-dynamic pinch experiment

At UCRL, Livermore, S. A. Colgate and H. P. Furth built a modified version of the fast (dynamic) pinch which was designed to extend the life of the pinched discharge prior to its breakup from instabilities. Known as the "screw-dynamic" pinch, its purpose was to suppress the development of the more rapid sausage-type instability, so that the somewhat slower kink-type instability would be the first to grow. To accomplish this goal, a straight pinch discharge tube was used, but with slightly helical grooves cut in the cylindrical return conductor outside the tube. In order to achieve

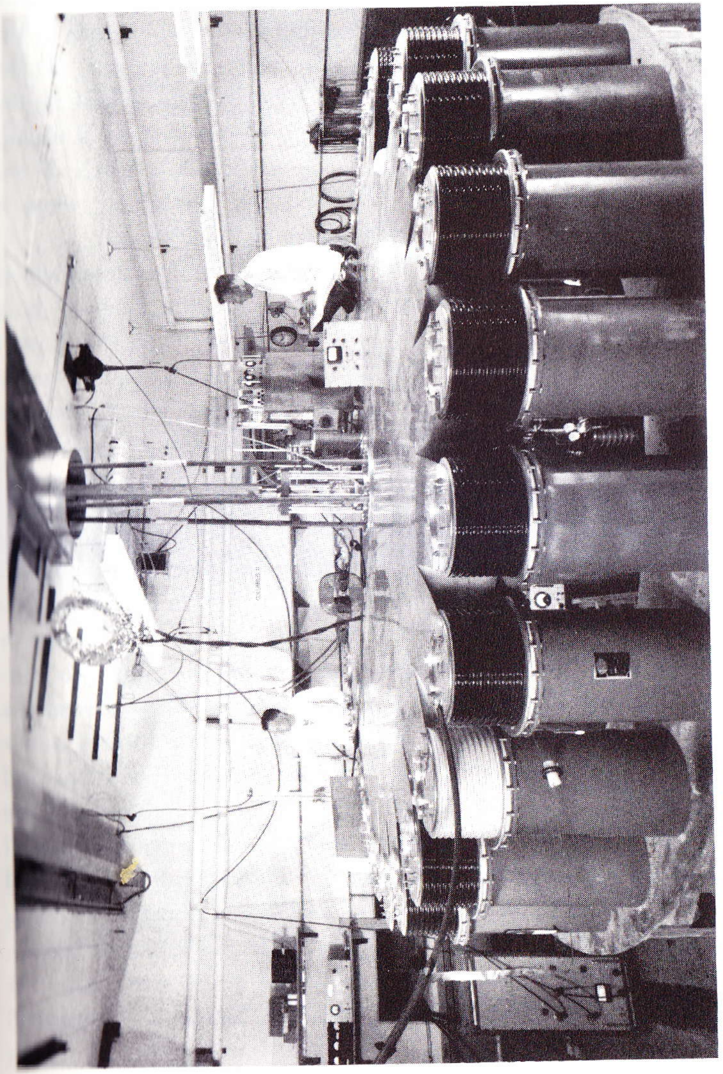

FIG. 10–3. THE COLUMBUS II EXPERIMENT. A set of high-voltage capacitors encircles the discharge tube at the center, thereby providing a system with low over-all inductance.

high temperatures from rapid formation of the pinch, no axial magnetic field is superimposed prior to the discharge (as in the case of stabilized pinches). At the time of discharge, however, the sudden surge of current in the external helical conductor produces a small axial magnetic field which, as a result of ionization of the gas in the tube, becomes trapped near the outer surface of the plasma. As the pinch forms, this field is compressed to high values. Thus, in the fully formed pinch, the plasma filament is surrounded by a sheath of axial magnetic field, which tends to inhibit the growth of the sausage-type instability. The final breakup of the pinch, when it occurs, will then be due to an instability of the kink type.

Experimentally, it was found that the pinch behaved roughly as expected, and that neutrons were produced at the time of kink formation. Because of the longer times associated with the growth of the kink instability, it is hoped that in the larger models now under construction the plasma can be brought to thermonuclear temperatures and densities before such instabilities can develop.

Tubular pinch experiment

Another interesting method of achieving quasi-stabilization, initiated in 1956 at UCRL, Berkeley, by W. R. Baker and O. A. Anderson, is the tubular or "triaxial" pinch. In this concept, shown in Fig. 10–4, the insulated discharge chamber lies between two concentric conducting cylinders. If a voltage is impressed between the top and bottom of the chamber, a current discharge is formed in the annular region, the return current dividing between the inner and outer conductors. The azimuthal magnetic field produced by the discharge and wall currents compresses the plasma into a coaxial cylindrical sheet of intermediate radius. Theoretically, a pinched discharge of this type, consisting of a cylindrical sheet of current, should be partially stable against the formation of kinks or bulges. Indeed, experiments showed that the triaxial pinch was stable for much longer periods than a simple pinched filament. Improved experimental models based on this concept are presently being developed.

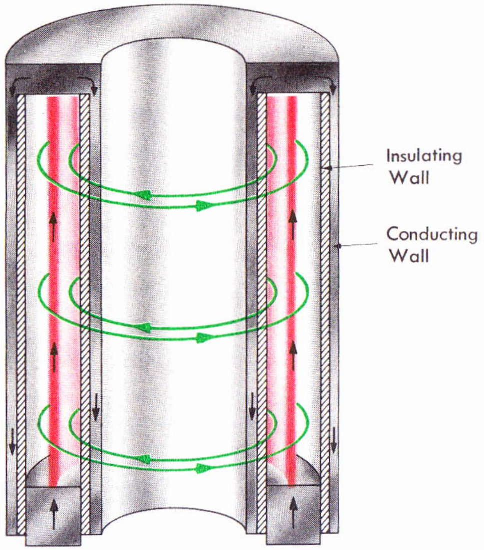

FIG. 10–4. TRIAXIAL PINCH. Voltage impressed between the top and bottom of the annular discharge chamber produces a current in the annulus. Azimuthal magnetic fields produced by the discharge and wall currents compress the plasma into a coaxial cylindrical sheet.

CHAPTER 11

THE STELLARATOR PROGRAM (PART II)

A. 1955 to Mid-1956

Concern over stability

At Princeton, the impact of the stability discussions in late 1954 was immediate and far-reaching. If the views put forward at that time were correct, they strongly implied that the stellarator was unstable. The future of the program as a whole was at stake.

The theoretical group, headed by E. A. Frieman, immediately concentrated its efforts on the difficult task of determining the explicit conditions of stability. As discussed in Chapter 9, the results of the extensive analysis which was carried out were far from encouraging. The stellarator configuration in its existing form certainly appeared to be unstable in theory; moreover, the computations showed rather surprisingly that it should be unstable for all values of β—that is to say, not only for high plasma pressures, but for low pressures as well. What was still undetermined was the rate at which the interchange instability would develop; there was, however, reason to believe that it would develop fast enough to destroy all hope of adequate confinement.

These results, later confirmed independently by others using different mathematical treatments, made it clear that a modification of the program was in order. Most pressing was the question of what to do about the Model C stellarator project. Early in 1955, pending the outcome of the theoretical studies, work had continued at Princeton toward specifying the characteristics of this sizable machine. Steps had been taken toward selecting a suitable industrial group to carry out its detailed design and possibly its construction. Nine companies had been provided full information on a classified basis concerning the stellarator program and had just submitted their proposals for undertaking the design. A decision was needed as to whether or not to proceed.

In mid-June, 1955, after a thorough re-evaluation of the stability question and upon the recommendation of both the Matterhorn group and the Steering Committee, the decision was made by the Director of the Research Division to defer further work on the Model C stellarator. In the face of the forbidding theoretical predictions, it was felt it would be folly to continue work on a project of this magnitude. Instead, effort should be concentrated on gaining further experience with the smaller B-type models.

The industrial groups involved were immediately advised of this decision and of the reasons for it. All of them agreed to consider their bids as valid for a period of six months in the event that the work be resumed during this time. Although the outlook for stability brightened materially during this period, the detailed design of the Model C stellarator was not begun until two years later.

Kruskal limit

Meanwhile, the experimental group at Princeton, under the direction of M. B. Gottlieb, was concentrating its effort on completing the Model B-2 stellarator and obtaining meaningful experimental results from the B-1 and B-64 models. The B-64* stellarator, developed by T. H. Stix, was a new experimental model (see Fig. 11-1) composed of standard components of straight and curved metal tubing, on which the magnetic field coils were wound directly and which could be readily clamped together to provide any desired shape. It thus possessed great flexibility and could be assembled or modified with relative ease.

One important result obtained from both these models was the experimental confirmation of theoretical predictions concerning a special type of instability in the stellarator. Theoretical studies by M. D. Kruskal had shown that if the axial current in a stellarator were to exceed a given value (which depends upon the twist of the figure 8, the tube diameter, and other factors), the discharge would become unstable and the plasma should escape immediately to the walls.

A useful, though not altogether accurate, way of visualizing the origin of this instability is the following. The axial current in the plasma will produce an azimuthal magnetic field of its own which will

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* This name developed from the fact that this particular figure-8 configuration, when viewed from the top, resembled a square. $(8)^2 = 64$; hence B-64!

(depending upon its direction) either increase or decrease the existing twist of the field lines resulting from the figure-8 configuration (see page 34). If the net twist during one transit of the tube is increased to 360° or, alternatively, decreased to 0°, the magnetic lines become degenerate and the system would be expected to become unstable.

In confirmation of the theory, experiments with the B-1 and B-64 models showed clearly that when the current resulting from the DC heating pulse exceeded the so-called "Kruskal limit," the discharge became violently turbulent and the plasma was rapidly lost to the walls. At that time, however, the discovery of this type of instability caused relatively little concern, since it was believed that the heating current in the stellarator could always be kept below the Kruskal limit.

Impurity difficulties

During the early part of 1955, the experimental program ran into a new stumbling block: impurities in the discharge. As pointed out on page 10, the presence of even minute amounts of high-Z materials can seriously increase the radiation and thus depress the temperature of the plasma. In the case of the B-1 and B-64 stellarators, the influx appeared to come from the walls during the discharge itself, and its effect proved to be very serious. While the electron temperature reached its predicted value of several hundred thousand degrees, the ion temperature (which should have reached roughly the same value) was an order of magnitude lower. Moreover, after a few hundred microseconds, the accumulating impurities within the discharge brought the electron temperature down to a fraction of its initial peak value.

There were two ways of overcoming this difficulty. One was to develop a very clean vacuum system by "baking" the walls of the discharge tube to remove occluded gases. This process would permit the production of a much higher vacuum than that which had been previously obtained (10^{-6} millimeter of mercury). The second possibility was to incorporate a "divertor" (see page 43) into the system, to prevent energetic particles of the plasma from striking the walls and ejecting impurities back into the discharge. Ideally, it would be advantageous to have both possibilities simultaneously (a clean

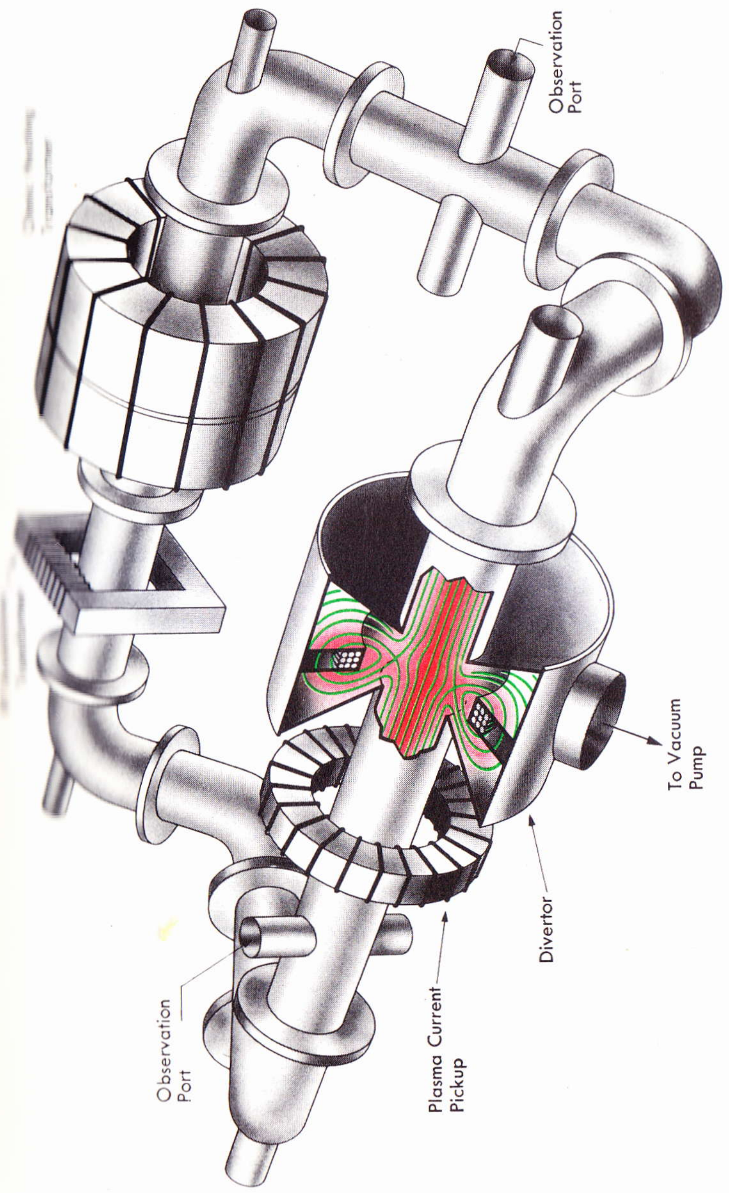

FIG. 11-1. THE B-64 STELLARATOR. Built of standard components, this flexible facility looks square when viewed from above. Looked at from the end, however, the characteristic figure-8 configuration may be seen. The drawing shows the divertor, transformer coils for inducing the heating voltage, and other components.

vacuum system working with a divertor), and intensive work began on both aspects of the problem.

Independent of all other developments, it was clear that the achievement of ultra-high vacua, already a bottleneck on the B-1 experimental program, would be of critical importance in future experimental models. An intensive effort to rectify this difficulty was initiated at Princeton under the direction of D. J. Grove. By adapting to large systems many of the principles developed by D. Alpert and at the same time developing some new ideas of their own, the group at Princeton succeeded, over a period of about a year, in improving the vacuum attainable in the B-1 stellarator by the impressive factor of about ten thousand (i.e., by mid-1956 vacua of the order of 10^{-10} millimeter of mercury could be readily achieved in large systems).

It was decided, on the other hand, that the most rapid way of testing the effectiveness of a divertor would be to incorporate one into the B-64 stellarator. The flexibility of this model permitted the modification to be made rather easily and simply. The results were most gratifying. With the divertor in operation, the ion temperature rose by a factor of about 10, to its proper value of several hundred thousand degrees.

B. Mid-1956 to 1958

Stabilization of the stellerator

While the above experimental work was in progress, Spitzer had been searching for possible ways of inhibiting the development of instabilities in the stellarator configuration. After considering and rejecting a number of approaches, he suggested early in 1956 that adequate stabilization could, in fact, be achieved by imposing additional magnetic fields upon the original confining field, in such a way as to strap the lines of force together, so to speak, in the manner shown in Fig. 11–2. There were a number of ways in which this could be accomplished in practice. One of the simplest was to add six current-carrying conductors which would entwine the discharge tube, as illustrated in Fig. 11–3. The magnetic field produced by these conductors would, in turn, provide a twist to the original field, as is also shown in the drawing. It turns out, however, not to be a

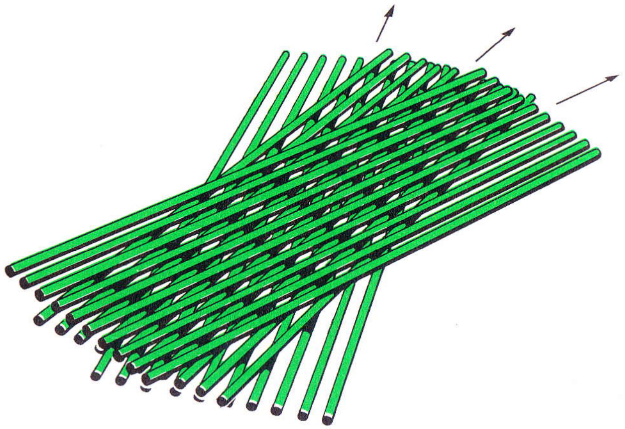

Fig. 11–2. Illustration of Shear Fields. The lines of force in one plane are twisted with respect to those in adjacent planes.

simple twist but—and this is the important point—a twist with "shear."

These shear fields may be explained in the following way. If one considers two lines of force lying at different distances from the center of the tube (e.g., those passing through points *a* and *b* as shown in Fig. 11–3b), it is found that they do not rotate together as they traverse the tube. At some distance farther along the tube, point *a* will have rotated to position *a*′, while point *b* will have rotated through some larger angle to point *b*′. Thus the outer lines of force overlie the inner ones and tend, in effect, to strap them down.

Following Spitzer's suggestion, the theoretical group at Princeton made a detailed study of the effect of shear fields upon stability. Their study showed that fields of this nature should theoretically be capable of preventing the growth of any instability, provided the value of β is not too high. Here then was a possible answer to the stability problem for the stellarator. While the maximum permissible value of β was not as large as desired,* it was nevertheless sufficiently high for the stellarator to be of practical interest.

Toroidal configuration; "Etude"

But the set of helical windings did more than resolve the problem of stability. It provided another very important function: a rotational transform to the confining field. As a result, it was no longer necessary to use a complicated figure-8 configuration. The addition of the helical windings made it possible to use a discharge tube having the much simpler shape of a toroid.

With a solution in hand for the instability difficulty (a solution which simultaneously provided a major simplification of the stellarator configuration) the outlook for this approach brightened considerably. Two models of a small experimental device, called Etude, were designed by T. Coor to compare the relative effectiveness of the two systems (figure-8 versus a torus with helical windings) and to study the behavior of plasmas in such systems. Since they employed a steady magnetic confining field, it was expected that these models would also be useful tools in basic plasma research.

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*The maximum permissible value of β depends upon the magnitude of shear of the magnetic field. For the system shown in Fig. 11–3, the value of β is limited to about 20 percent. Above this value, theory predicts the system to be unstable.

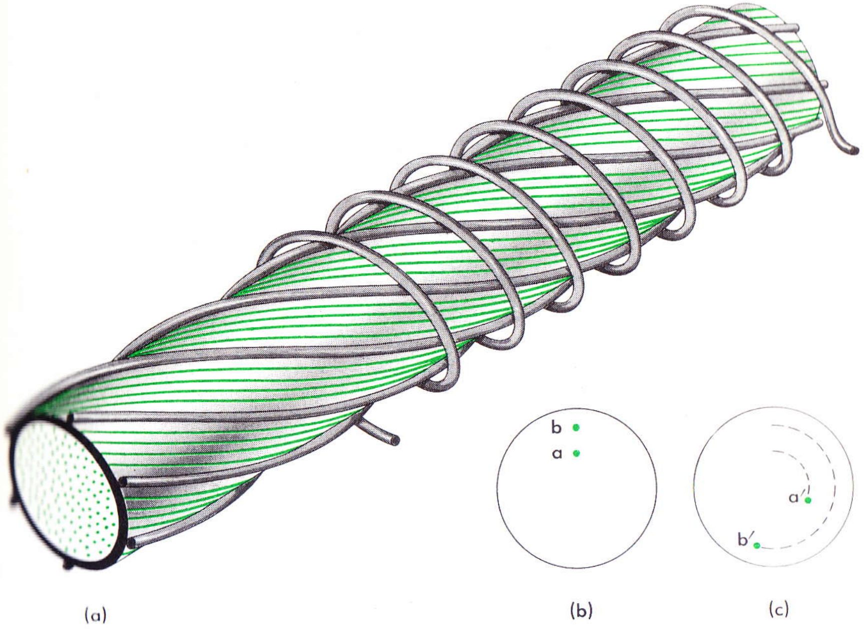

Fig. 11–3. Stabilizing Windings on the Stellarator. Part (a) shows a section of the stellarator tube, with the six helical stabilizing windings just outside the tube. The combination of their field and that of the usual confining coils gives a twist to the lines of force as they pass about the tube. (b) Cross section of the tube, showing the position of two illustrative lines of force passing through points *a* and *b*. The relative positions of these same two lines farther along the tube is shown in (c). The line of force farther from the tube center has rotated through a larger angle than that which is closer.

Experimental difficulties

The situation, however, was still far from optimistic. Except for the above theoretical results on stability, progress in the stellarator program was somewhat slow and at times discouraging. A succession of developments occurred which required the modification of existing experimental models or the construction of new and improved versions.

The Model B-2 stellarator—designed to achieve plasma temperatures of several million degrees by several successive methods of heating (radiofrequency voltage, followed by a DC voltage pulse, followed by magnetic pumping)— had never really operated successfully. The difficulty: impurities. Having been installed prior to the improvement in vacuum technology, the walls of the tube emitted a flood of impurities during the discharge which cooled the plasma faster by radiation than it could be heated by the relatively slow process of magnetic pumping.

Because of these and other difficulties, it was finally decided to construct an improved version, Model B-3 (Fig. 11–4), capable of incorporating all the major improvements developed during the past several years: ultra-high vacuum system, divertor, improved heating techniques, and helical stabilizing windings. This device, designed by a group under R. G. Mills, started operation early in 1958, with magnetic fields up to 40,000 gauss.

Cyclotron-resonance heating

In the meantime, T. H. Stix proposed in 1957 a modified version of magnetic pumping which gave promise of heating the plasma ions much more rapidly and efficiently than before. This method, called "cyclotron-resonance heating," involved alternately compressing and expanding the plasma in a special way at a frequency close to the so-called cyclotron frequency* of the ions. Heating of the plasma at the cyclotron frequency had been suggested several times pre-

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* That is, the natural frequency of rotation of the ions in a magnetic field. It is given by

$$f_c = Be/2\pi M,$$

where B is the magnetic field strength in which the ions find themselves, and e and M are their charge and mass respectively.

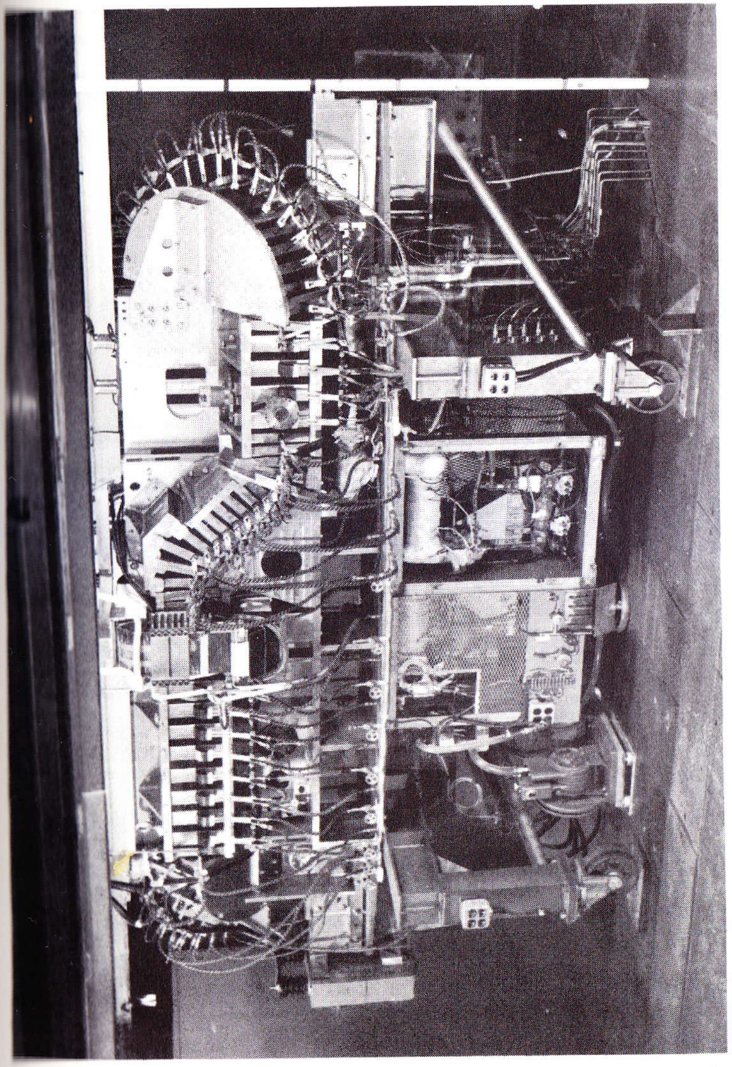

Fig. 11–4. The B-3 Stellarator, showing the characteristic figure-8 configuration. This model also possesses helical stabilizing windings which may provide additional rotational transform.

viously but was rejected because of charge separation difficulties. In the scheme proposed by Stix, this difficulty is overcome by incorporating two heating units side by side along the stellarator tube and operating them in opposite phase. Extensive theoretical analysis indicated that for a small-diameter plasma at low β this technique should heat the gas much more rapidly than that of magnetic pumping. To test out this idea as rapidly as possible, the B-64 stellarator was modified (to B-65), the necessary equipment was installed, and successful application of this heating technique at very low power levels was carried out early in 1958.

Indication of instabilities

Perhaps the blackest cloud on the horizon at this time resulted from some of the experiments carried out with the model B-1 stellarator. Early in 1956 this model had been rebuilt with an improved vacuum system in order to minimize the impurity difficulty; since then it had continually proven to be one of the most useful and reliable devices for studying plasma behavior. But now experiments with this model indicated that the plasma was misbehaving during the heating process. Specifically, the confinement of the plasma was poor during this period and there was evidence that numerous particles were being lost to the walls, perhaps through some new sort of instability of electrostatic origin.

As pointed out on page 107, violent instabilities might be expected in the stellarator for sufficiently large currents within the plasma, that is, for currents above the so-called "Kruskal limit." In the present experiments, however, the currents during the heating process were kept well below this limit, and still the system appeared to be somewhat unstable. The exact origin of this difficulty was not understood even early in 1958. There was, however, reason to believe that "runaway" electrons, produced by the unidirectional voltage pulse, might be responsible. Steps were accordingly taken to modify the heating process so that the number of runaway electrons would be minimized.

Reinitiation of work on the Model C stellarator

In spite of many remaining difficulties, the over-all outlook for the stellarator approach appeared, by 1957, to have improved markedly

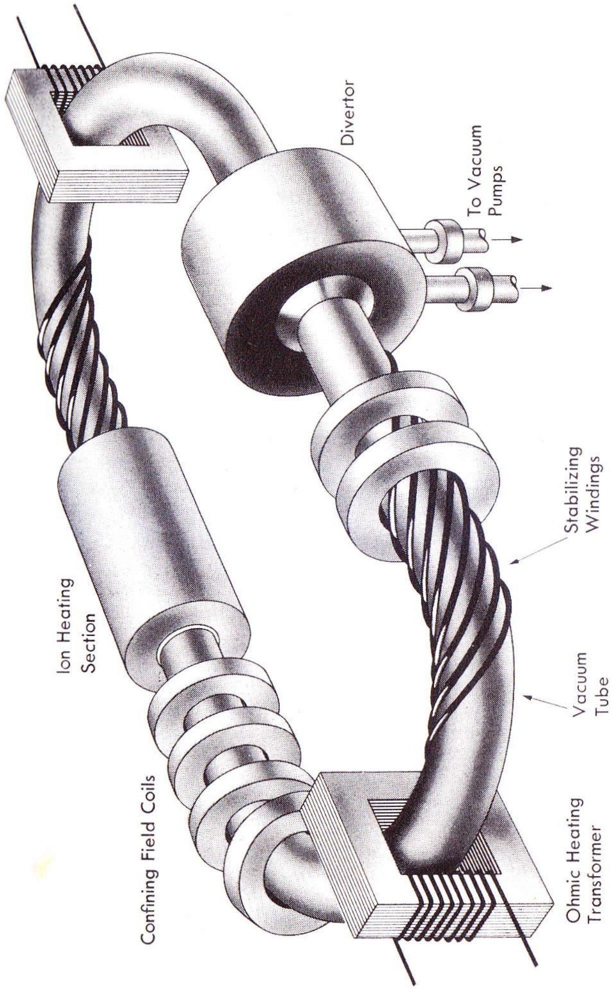

FIG. 11-5. THE MODEL C STELLARATOR, built to test components for a full-scale device and to study the properties of high-temperature plasmas. (The confining field coils and stabilizing windings actually go around the entire tube. Some were omitted in the drawing to show detail.)

over the preceding two-year period. The problem of interchange instability, which had been responsible for the cancellation of the Model C effort in 1955, had been resolved, in theory at least, by the development of shear fields. There was even reason to believe that the shear fields would inhibit the growth of the newly discovered electrostatic-type instabilities. As an important by-product of the stability work, the stellarator configuration had been simplified from a figure-8 shape to a torus. The impurity difficulties had been largely overcome by means of divertors and improved vacuum techniques. A more powerful method of heating (cyclotron resonance) had been developed, replacing the slower method of magnetic pumping.

On the whole, the progress that had been made appeared to justify reinitiating work on the design and construction of a modified Model C stellarator. This model had, from the outset, been planned as a large but flexible research tool, capable not only of testing more or less to scale many of the features of a full-size stellarator, but (even more important) of producing high-temperature plasmas and studying their properties in detail. A sketch of the modified version of the Model C stellarator is shown in Fig. 11–5, and its characteristics are given in the stellarator chart at the back of the book. Designed to yield plasma temperatures of about one hundred million degrees and (with later modifications) β-values of several percent, this model seemed an appropriate and essential extension of the work which had been accomplished up to that time.

Following Commission consideration and authorization of the project, proposals were solicited again from the same companies that had responded before. On the basis of these proposals, a contract for the detailed design and construction of the Model C stellarator was awarded to a combined group from Allis-Chalmers and Radio Corporation of America (RCA). A section of land not far from the existing Matterhorn buildings was provided by Princeton University as a site for the laboratories required. Upon completion of all the various administrative arrangements, work began in earnest in the fall of 1957 on this large and complex experimental model. Its operation, presently scheduled for late 1960, should yield important information on the behavior of high-temperature plasma—information which will hopefully carry the Sherwood program a major step forward toward its goal.

CHAPTER 12

THE MAGNETIC MIRROR PROGRAM (PART II)

A. From 1955 to Mid-1956

Impact of the 1954 conference

As pointed out in pages 85–86, the results of the 1954 conference (and the subsequent theoretical confirmation of the views on instability expressed there) seemed to deal a severe blow to the magnetic mirror approach. The region between the mirrors, where the lines of magnetic force are concave toward the plasma, appeared unquestionably to be unstable. Evidence was strong that the lines of force would tend to snap inward, interchanging position with the outward pressing particles of the plasma and thereby permitting the plasma to escape to the walls of the discharge chamber. On the basis of these theoretical considerations, the outlook was rather discouraging. There were, in fact, many who felt that there was little justification for continuing work on this approach.

On the other hand, examination of available experimental data showed that the picture was perhaps not so bleak as it initially seemed. A model known as Q-cumber, built during 1954, with a high mirror ratio to provide information on the rate of diffusion of ions across a magnetic field, had just come into operation. Although the data available at that time were admittedly scanty, there seemed to be no evidence whatsoever that plasma particles were escaping to the walls at an abnormally rapid rate, as would be expected if the configuration were unstable.

Experimental work on the stability question

The attention of the Livermore group was immediately concentrated on acquiring further information on this question, using existing experimental models. Interest that had earlier been devoted to achieving high plasma temperatures was now redirected toward making careful measurements of the confinement time of a plasma in mirror geometry. While many months were consumed in acquiring the experimental data, the final results were encouraging.

Specifically, the results with the Toy Top and Table Top models demonstrated that the plasma was being confined by the magnetic field configuration for many milliseconds—periods several hundred times longer than would be expected in the presence of instabilities. In addition, an extensive set of measurements carried out with the Q-cumber device confirmed the earlier results and showed positively that the rate of loss of the plasma was roughly consistent with the normal rate of diffusion through collisions, rather than with the much more rapid rate that would have been associated with instability growth.

It was of course recognized that in all these experiments the ratio of plasma pressure to magnetic pressure was very low; in each case, the value of β was 1 percent or less. It was thus of great interest to obtain similar data for higher β-values. Being defined as $nkT/(B^2/8\pi)$, β could be increased either by increasing the temperature and density of the plasma, or by decreasing the value of the magnetic field in the region of interest. Since the lack of a suitable ion source precluded the first possibility, a modified Q-cumber experiment was built, having very weak magnetic fields in the central region, which would permit an increase in the value of β to about 5 percent. The rate of plasma loss was again measured, and again there was no evidence of instabilities.

These important results, while highly encouraging, were also puzzling from a theoretical point of view. A number of qualitative explanations were advanced in an attempt to understand the apparent discrepancy between theory and experiment. It was pointed out, for example, that the magnetic configuration which had been so carefully analyzed was, at best, only an approximation to the more complex shape of magnetic field lines within the mirror machine. A matter of perhaps even greater importance was that in actual operation the two ends of the mirror machine are closed with metal plates through which the magnetic lines pass. It was believed that these metal plates might well be instrumental in stabilizing the magnetic configuration, either by "tying down" the lines of force passing through them and inhibiting their motion with respect to one another or by providing a means of short circuiting any voltage buildup within the chamber, thereby destroying the mechanism of instability growth.

Ion source work

In any case, the encouraging experimental results, coupled with the above tentative explanations, temporarily allayed further concern over instabilities in the mirror machine, and attention was turned once more to the problem of increasing the temperature and density of the plasma.

A great deal of work had been carried out, in the interim, on the development of suitable injectors for the mirror program. The continuous ion source which had been developed at Oak Ridge for use at Livermore had been completed and delivered. By this time, however, detailed computations carried out by the theoretical group at Livermore had shown that the angle of acceptance of ions injected into a mirror machine was appreciably smaller than had been originally believed. As a result, it was found that this rather large ion source would likely be far less satisfactory than had been hoped.

In compensation, however, developmental work with the small titanium-type pulsed sources had been rather encouraging. By adapting some of the basic principles of the Oak Ridge injector to the small pulsed source, K. Ehlers had succeeded in increasing the energy of emitted ions to about 5 kilovolts, even in the presence of nonhomogeneous and time-varying magnetic fields. The operation of these sources clearly required a discharge chamber several feet in diameter, so that the energetic ions, when injected at low magnetic field strength, would not strike its walls. Even the chamber of Table Top was too small. As a result, work began on the design and construction of a larger model known as Felix. (See page 126.)

B. MID-1956 TO EARLY 1958

Up to this time, essentially all the work involving mirror confinement of a plasma had been carried out at UCRL, Livermore. This magnetic mirror program (or "Pyrotron" program as it now was called) had been directed almost entirely toward the problem of injecting and trapping ions of low to moderate energy into a rising magnetic field, and heating them to thermonuclear temperature by the process of adiabatic compression.

During the period 1956–58, however, different but related projects involving magnetic mirror confinement were begun at other laboratories. In this section, we shall first discuss the continuation of the Pyrotron program at UCRL, Livermore, and then the related work on "rotating plasmas," which was carried out at a number of different laboratories.

PYROTRON PROGRAM

Experiments with Table Top II

By mid-1956, the technique of producing a highly ionized and relatively pure burst of low-temperature plasma* within the Table Top chamber was much improved over earlier work. An extensive series of measurements was undertaken by F. C. Ford to determine the degree of compression and heating that could be achieved in an improved one-stage machine, called Table Top II. Plasma was injected when the field in the central region was very low, and the field was then pulsed to its full strength of 50,000 gauss. It was observed that x-rays were emitted over periods of many milliseconds, giving evidence that at least a portion of the plasma had been strongly heated and was being confined in a stable manner for periods of this length.

These x-rays were found to originate from energetic electrons that had slowly escaped through the magnetic mirrors and had followed along the lines of flux to vacuum chamber walls outside the mirrors. Thus, by measuring the x-ray intensity at various positions along the chamber walls, it was possible to "map" the origin of the electrons back into the discharge chamber and determine the density distribution of the compressed plasma. Measurements made in this way (and also with probes) showed that the hot plasma was in the form of a thin spindle in the center of the chamber. From the energy distribution of the electrons, their temperature was deduced to be very high—tens of millions of degrees. This encouraging result was definite evidence that the heating processes were sufficient to overcome radiation losses, even when appreciable impurities were known to be present.

Three-stage Toy Top (Fig. 12–1)

Meanwhile, F. H. Coensgen, in an effort to obtain still greater compression and heating of the plasma than had been possible in Toy

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* In the Table Top and Toy Top experiments, the energy of injected ions was only about 5 ev.

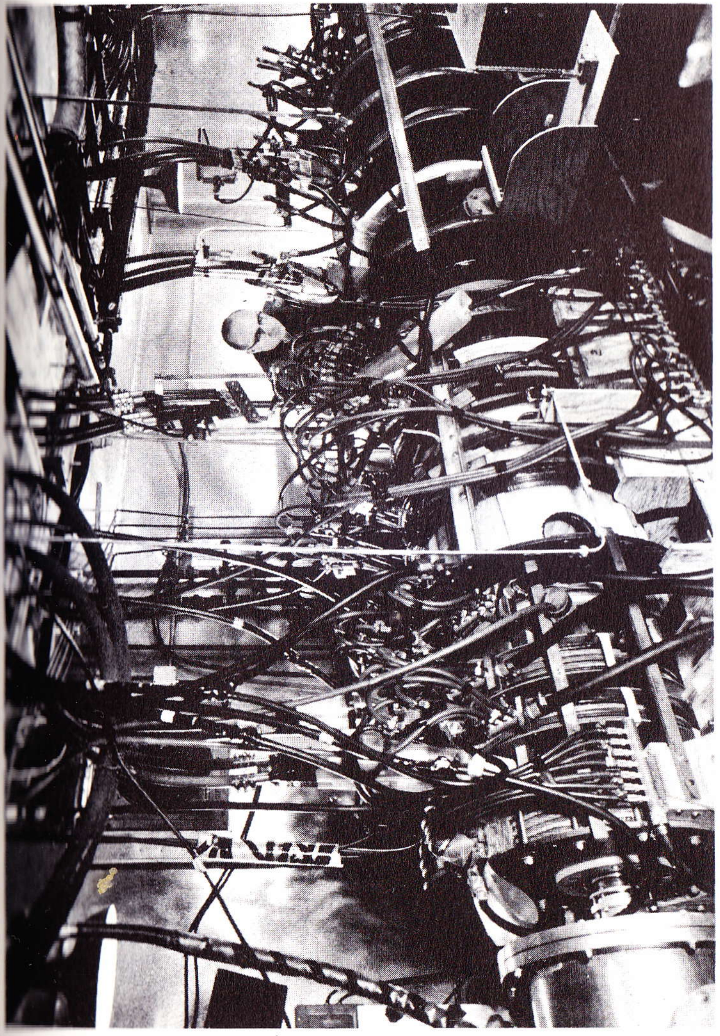
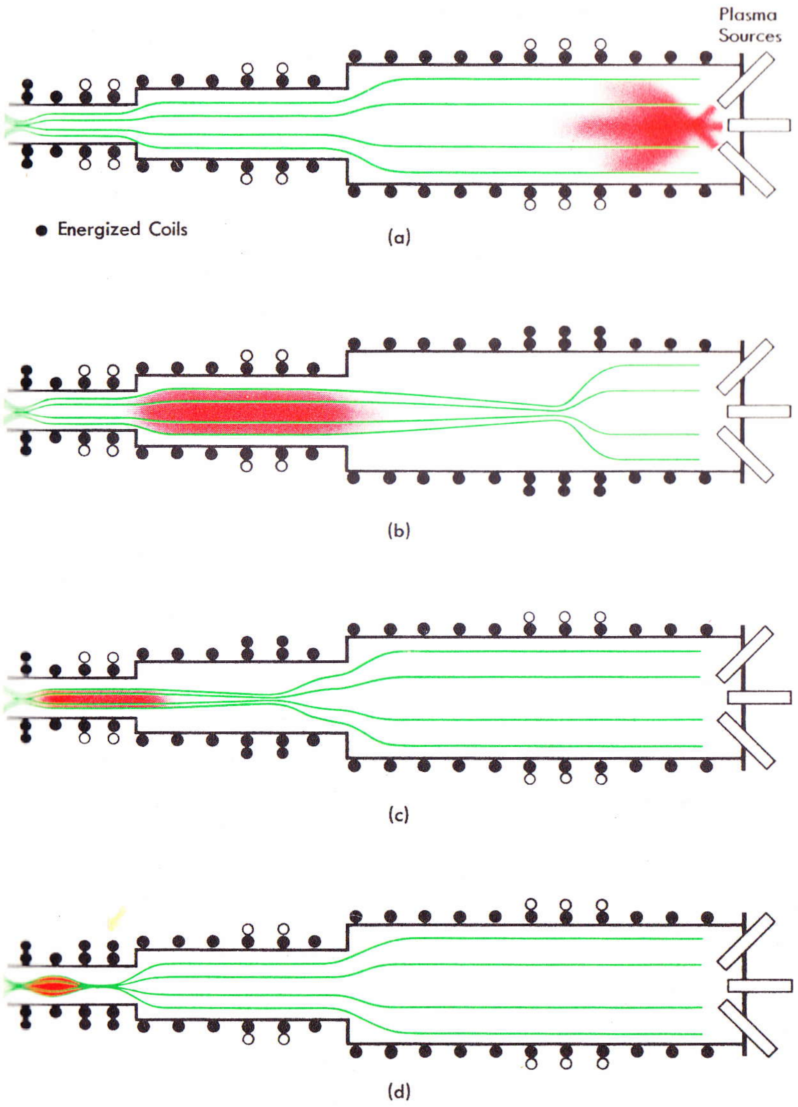


FIG. 12–1. THREE-STAGE TOY TOP. Plasma is injected into the chamber at the right, then compressed and transferred successively to the chambers in the center and at the left.

FIG. 12–2. THREE-STAGE TOY TOP MODEL. (a) Plasma is injected into the large chamber from ion sources at the right. (b) Partial compression of the plasma occurs when other coils around the chamber are energized, and the plasma is transferred to the second section. (c) Additional coils around this section are now energized, compressing and heating the plasma still further and transferring it into the third section. (d) Final compression occurs when the coils of the third chamber are energized. By this sequence, it is possible to produce a high-temperature plasma of rather high density. Magnetic mirrors inhibit the loss of plasma out the tube ends.



this device, the application of radial electric and transverse magnetic fields, in the manner shown in Fig. 12–3, causes the plasma particles to precess rapidly about the central axis. There is a momentary surge of current when the radial voltage is first applied; it stops flowing, however, as the plasma acquires rotational energy. The effect of the rotation is to bow the lines of the magnetic field in the manner shown, thereby creating a sort of magnetic trough which inhibits the escape of the plasma particles to the side walls. Said another way, the centrifugal force associated with plasma rotation tends to keep the particles away from the axis and to trap them in the region of bulging magnetic field.

Experiments with Homopolar gave positive evidence of plasma rotation and demonstrated that the plasma could be confined in this manner for surprisingly long periods of time (80 microseconds or more). It was clear that if adequate methods of plasma heating could be found the rotating plasma concept might even have potentialities as a thermonuclear device. One possible method of heating might arise from the conversion (through viscosity effects, say) of kinetic energy stored in plasma rotation to random thermal energy. Work was begun on larger experimental models to explore this possibility in greater detail.

Other developments; Ixion

In the meantime, several other groups undertook experiments using crossed electric and magnetic fields. Early in 1957, J. D. Gow, working independently at Berkeley, built a device having a configuration not unlike the early Oak Ridge work (pages 67–68). High electric voltages were applied, and the resultant neutron production was studied.

Stimulated in part by the work of Gow, a group at Los Alamos under the direction of K. Boyer built an experimental model known as Ixion (Fig. 12–4) which combined various features of rotating plasmas, magnetic mirror, and plasma arcs for applying electric potentials. In this device, a central plasma electrode is created by injecting a pulse of ionized deuterium gas along the axis from the left into the discharge chamber. A transverse electric field is then applied between the plasma electrode and an outer cylinder. The presence of an axial magnetic field (having a mirror configuration)

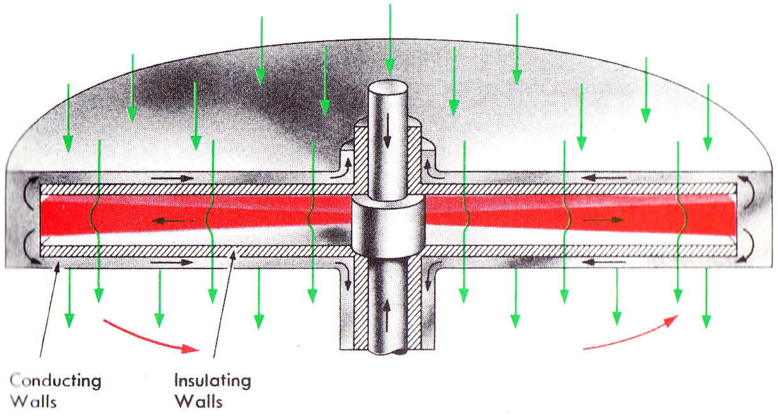


FIG. 12–3. HOMOPOLAR DEVICE. In addition to the axial magnetic field, an electric field is applied between the inner and outer radii, or the pancake-shaped annular chamber. The combination of fields causes the plasma as a whole to rotate. Its centrifugal force bows the magnetic lines of force and the plasma is thereby confined in a sort of magnetic trough.

then causes plasma ions to precess about the axis. In order to provide rotation of the plasma as a whole, special provisions were made to ensure that the high transverse voltage was distributed uniformly across the plasma, rather than as a sheath near one of the electrodes.

Theoretical studies carried out independently at Los Alamos and Livermore had confirmed that if a plasma were made to rotate sufficiently rapidly in a magnetic mirror field, the centrifugal force associated with such rotation would enhance the effect of the mirror and the loss of particles through them should thereby be greatly reduced. It was found that, to be effective, the energy of rotation of the plasma particles should be large compared with their thermal energy.

Experimental work with Ixion gave preliminary evidence of plasma rotation and of enhanced plasma confinement. As a result of the high applied electric voltages, neutrons were expected and observed. However, the temperatures of the plasma as a whole appeared to be suppressed by the presence of a serious influx of impurities, apparently emanating from the walls of the discharge chamber.

There was nevertheless hope that if this difficulty could be overcome the rotating plasma concept might be an effective method of enhancing the confinement of a hot plasma.

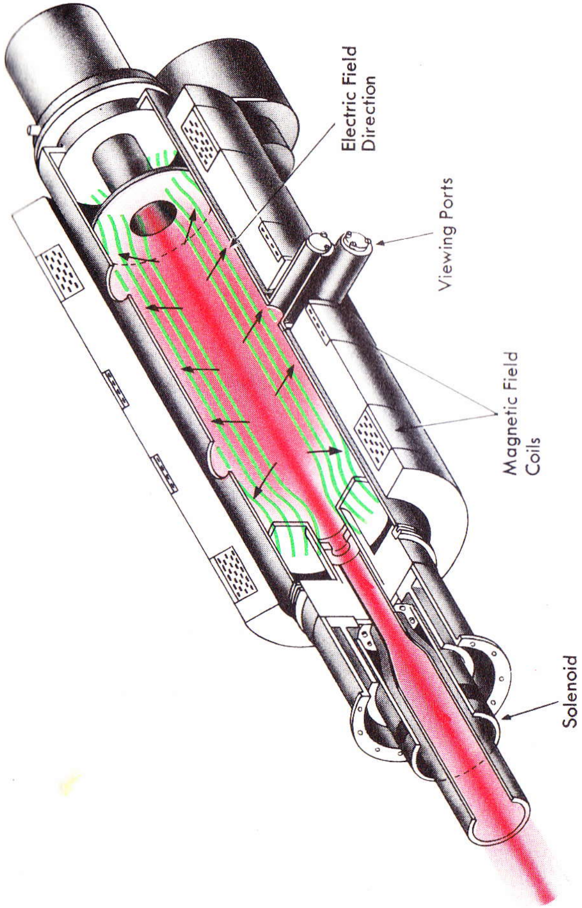


FIG. 12-4. IXION. In this model, a magnetic mirror configuration is used to provide plasma confinement. A radial electric voltage is established between a central arc and the outer wall of the discharge chamber, thereby creating an energetic plasma rotating about the axis. If sufficiently rapid, the rotation should enhance the effect of the magnetic mirrors.

CHAPTER 13

THE MOLECULAR ION IGNITION PROGRAM

In addition to carrying out the projects discussed in Chapter 6, the Sherwood group* at the Oak Ridge National Laboratory had been seeking for some time a new approach to the Sherwood field. A number of concepts had been studied in some detail, but none appeared sufficiently firm theoretically to warrant a strong experimental program.

High-energy injection

One of the ideas which appealed strongly to the Oak Ridge group, however, was to approach thermonuclear conditions from the high-energy, rather than the low-energy, side. Instead of starting, as in the other projects, with a rather large assembly of "cold" (or even "lukewarm") particles and attempting to raise their temperatures as a group to thermonuclear values, the interest at Oak Ridge was in many respects just the opposite. Their plan was to start with a beam of particles having energies *already* in excess of that needed for thermonuclear reactions and, by injecting and trapping them in a confined region, build up their densities to values of thermonuclear interest. In this way they hoped to "ignite" the plasma and produce a self-sustaining thermonuclear reaction.

The concept of high-energy injection had already been considered several times in the past, but no satisfactory method had been found for accomplishing this goal. The major problem was how to trap high-energy particles in the strong, steady magnetic fields required for their confinement. It is an axiom of physics that any particle injected into a static magnetic field configuration will not be trapped, but will eventually come back out unless its orbit is somehow changed while it is within the field.

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* This group, recruited by E. D. Shipley, consisted in the main of several Oak Ridge consultants—A. E. Ruark, E. Creutz, L. P. Smith, and H. Snyder—together with a few of the full-time laboratory staff.

Molecular ion dissociation

One possible solution to this difficulty, proposed independently in 1955 by J. S. Luce at ORNL and H. F. York at UCRL, was to inject a beam of high-energy *molecular* ions transversely into a strong and steady magnetic field and attempt to dissociate (break up) such particles before they came back out. The dissociation of a molecular ion would produce an atomic deuterium ion and a neutral deuterium atom (or possibly two atomic deuterium ions and an electron). Symbolically, these reactions may be written

$$D_2^+ \rightarrow D^+ + D^0,$$

$$D_2^+ \rightarrow 2D^+ + e^-.$$

Since the mass of an atomic ion is only half that of a molecular ion, its radius of curvature would be only half as large, and it could therefore be effectively trapped in the magnetic field. Figure 13–1 shows diagrammatically the paths these particles would follow if the molecular ions were to be dissociated at point *a*.

The problem was to find a suitable mechanism of breakup. At first it was thought that it might be possible, simply by collisions between the molecular beam and the residual gas atoms in the vacuum chamber, to build up a circulating ion beam of increasing density, which in turn would lead to further dissociation of the molecular beam. Calculations showed, however, that this mechanism was far from adequate; a much more efficient method of initial breakup was required.

During the ensuing months, J. S. Luce, A. E. Ruark, and others studied a number of different methods of dissociation. One possibility, suggested by Luce, was to use an arc discharge of one type or another for this purpose. As a result of his experimentations, a totally new type of carbon arc was discovered, more or less fortuitously, in the early part of 1956. Subsequent measurements showed that this arc had an unexpectedly high efficiency for dissociating a beam of molecular ions.

Here, then, were the makings of a promising approach to the production of controlled thermonuclear reactions. A high-energy beam of molecular deuterium ions would be injected into an appropriate confining field, for example a magnetic mirror configuration. In passing through a carbon arc established within the field, it would be dissociated in large part into atomic deuterium ions which would then be effectively trapped between the mirrors. As the trapped ions built up in density, their motion, highly ordered at first, would rapidly become randomized as a result of several processes, e.g., precession in the magnetic field and interactions among the particles themselves. In this way it should be possible, in principle, to form a high-temperature, high-density plasma of practical thermonuclear interest.

Particle losses; burnout

It was clear, however, that the initial buildup of ion density might not be easy. For this to occur, the rate of loss of hot ions from the confined region would have to be less than the rate of addition of new ones. The rate of input of new trapped ions would depend on the intensity of the molecular ion beam and on the breakup efficiency of the arc. The rate of loss of hot ions, on the other hand, would depend on a number of factors, among them the adequacy of the magnetic confinement and, above all, the probability of charge exchange between the energetic ions and any neutral gas particles that might exist within the chamber.

To prevent charge exchange losses from dominating the process, it would be necessary to keep the neutral gas density to a very low value. Theoretical studies by A. Simon and others showed that it should be possible to reduce this density drastically by a process known as "burnout." If the injected beam intensity could be made high enough and the background pressure low enough (by extensive vacuum pumping), a critical point should be reached at which the trapped ion beam would ionize the neutrals as rapidly as they entered the plasma region. Beyond this point, a snowballing process would occur: the neutral density would decrease, permitting an increase in ion density, which in turn would lead to still further decrease of neutrals. Thus the achievement of burnout would result in rapid buildup in ion density. The hot ions, now persisting much longer in the system, would then degrade somewhat in energy as a result of energy transfer to colder electrons and ions which may be present. Concurrently, their motion would randomize, and a high-temperature, high-density plasma would be formed.

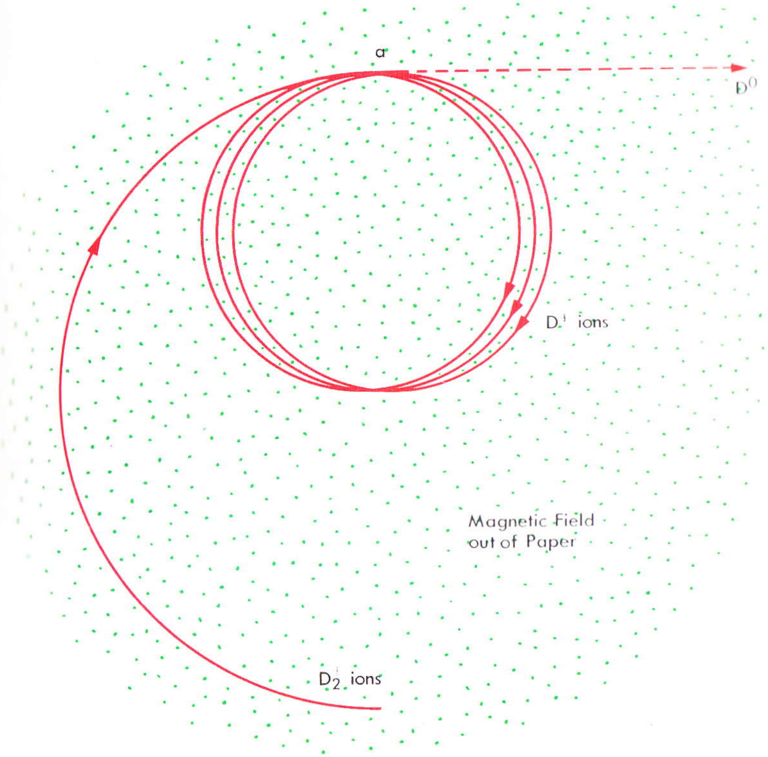

FIG. 13–1. MOLECULAR ION BREAKUP. A high-energy molecular deuterium ion beam injected perpendicularly into a static magnetic field will follow a curved path, as shown. If at some point *a* the molecular ions are made to dissociate, the resulting atomic ions will follow a curved path having half the radius of curvature of the original path and may then be trapped in the magnetic field. The neutral atoms will, of course, escape.

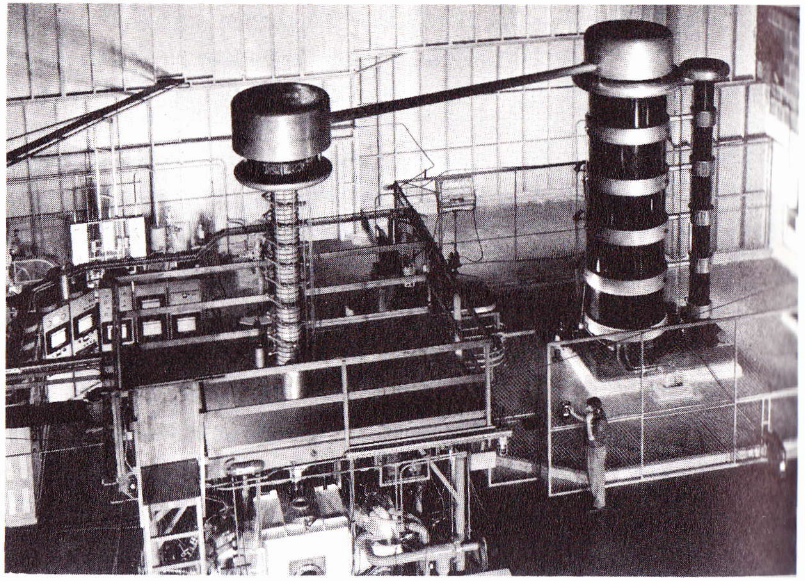

FIG. 13–2. THE DCX DEVICE. Molecular ions from the accelerator in the upper left are injected into the discharge chamber below, where they are dissociated and trapped in a mirror field. At upper right is the high-voltage generator for the accelerator.

The DCX experiment

As a first step toward the above goal, work on an experimental model known as DCX was begun in the fall of 1956, under the direction of E. D. Shipley and P. R. Bell. An intense carbon arc was established near the axis of a magnetic mirror configuration, as shown in Fig. 13–3. A beam of molecular ions, having energies of 600 kev,* was injected transverse to the steady-state field and passed

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* Since the probability of charge exchange decreases with energy, it is desirable to use as high an energy of injected beam as practical, consistent with other requirements (such as high intensity beam, high breakup efficiencies, reasonable magnetic field strengths, and adequate final plasma temperature). With this injected energy, calculations showed that the final plasma temperature should be in the neighborhood of a billion degrees

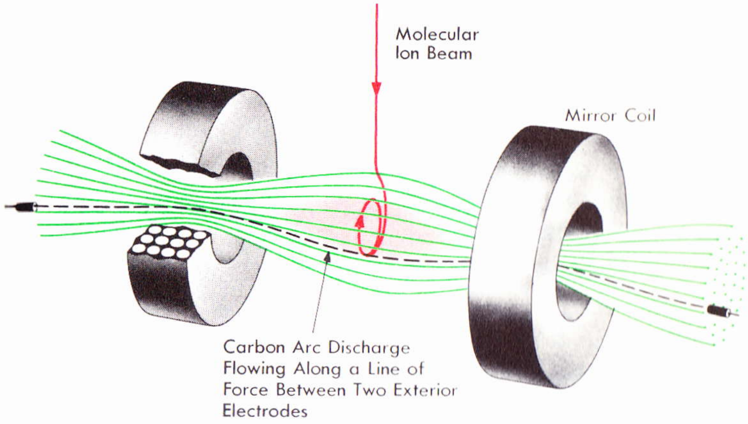
Molecular Ion Beam
Mirror Coil
Carbon Arc Discharge Flowing Along a Line of Force Between Two Exterior Electrodes

FIG. 13–3. THE DCX EXPERIMENT. In this device, a carbon arc discharge is used to cause a high-energy molecular ion beam to dissociate. The resulting deuterons are then trapped in the magnetic mirror configuration.

through the arc, thereby becoming partially dissociated. The 300 kev atomic deuterium ions resulting from this breakup were then trapped and confined between the mirrors.

The purpose of this first experiment was simply to determine the degree of trapping of the beam and the possibility of achieving burnout, with a consequent buildup of plasma density. The results of preliminary experiments were unquestionably encouraging. Breakup efficiencies as high as 40% were achieved, and the dissociated ions were observed to circulate for many milliseconds, on the average, prior to escape. As of early 1958, burnout had not yet been achieved, but calculations indicated that only relatively small improvements in operating conditions should be required to reach this immediate goal.

Future plans

While the outlook for attaining burnout (and thereby producing a plasma of thermonuclear temperature in DCX) appeared promising, it was recognized that the strength of its steady confining field (about 10,000 gauss) would not be sufficient to retain the charged reaction products of thermonuclear burning, and that DCX would therefore be incapable of supporting a self-sustained reaction. Thus, even while DCX was being assembled, preliminary design work was begun on a larger and improved model known as ORION. In this model it was planned that after burnout had been achieved and an appreciable plasma density built up, the arc and molecular ion beam would be turned off. The magnetic field would then be abruptly increased to a value sufficiently strong to confine the reaction products. It was hoped that from then on it would be possible for thermonuclear temperatures to be sustained, even if the system were fed with much lower-energy fuel.

CHAPTER 14

THE CUSPED GEOMETRY PROGRAM

Picket-fence and cusped geometry

One of the conclusions which developed as an aftermath of the Princeton conference in 1954 was that magnetic configurations with lines of force curving away from the plasma should be inherently stable, whereas those curving toward the plasma should tend to be unstable. There was, at that time, growing concern in the minds of many people as to whether adequate stability could be achieved with *any* of the approaches then under development. As a result, considerable thought was given to entirely new magnetic configurations, such as Picket Fence, in which the lines of magnetic force curve everywhere away from the plasma, and which thus offered hope of stability.

Various modifications of this idea were explored at Los Alamos and New York University. In particular, a careful study was made of a magnetic configuration similar to that shown in cross section in Fig. 14–1(a). Such a configuration could be produced, for example, by two coils in which the current would be in opposite directions so that their magnetic fields would oppose each other. (If the current in the two coils were in the *same* direction, the magnetic fields would resemble the mirror configuration.) Computations indicated that a system of this type would very likely be stable; the big question, however, was whether the particles would be adequately confined, or whether they might leak out rapidly by squeezing between the lines of the magnetic field in plane A-A (Fig. 14–1b). As discussed earlier, theoretical work at Los Alamos indicated that in a *low*-density plasma the individual particles would leak out at an intolerably fast rate.

The NYU group, however, studied a somewhat different situation, which proved to be more promising. Under the leadership of H. Grad, a theoretical analysis was made during 1955 of the modified version shown in Fig. 14–1(c), in which a plasma of *high* density (or, more exactly, of high β) is confined in a finite domain having cusps. For such a plasma, there is a sharp boundary between the plasma and the magnetic field. Rather surprisingly, calculations showed that the rate of particle leakage for a cusped geometry of this type was much lower than for the Los Alamos case. In fact, it was found that the plasma confinement at thermonuclear temperatures, while not as good as desired, might still be adequate to make this configuration of practical interest.

Here, then, was a possible approach offering the two important features of inherent stability and adequate confinement.

Problems encountered

Offsetting these advantages, however, were several new and serious problems to be faced. How, for example, is it possible to create initially a configuration of this type, with sharp boundaries between plasma and field? Is it not essential to begin with a low-density plasma and then raise it up to high values? If so, is not the leakage intolerably great during the transition period until the boundary is formed? Even assuming that by rapid injection and heating it is possible to establish a sharp boundary with a high-β plasma in the center, will this boundary not tend to become diffuse in time, with consequent increase in leakage rate?

These were the kinds of difficult questions to which answers (or at least informed guesses) were required before an experimental effort could justifiably be initiated.

Over the ensuing months, a careful study was made of these matters by J. Berkowitz, K. O. Friedricks, H. Goertzel, H. Grad, and others, not only for the above configuration, but for numerous other cusped geometries as well. The rate of particle loss as a function of temperature was analyzed, and several ways were found for reducing such losses at thermonuclear temperatures. The stability of such systems was proved mathematically (on the assumption of sharp boundary between plasma and field). The problem of producing a sharp initial boundary was, in turn, largely resolved by subsequent developments in shock techniques (see Chapter 15). Leaving aside the complex problem of whether such boundaries, once established, could subsequently be maintained, the over-all outlook for this approach appeared to be quite promising. Studies were even carried out on the size and characteristics of a power-producing thermonuclear reactor based on the cusped geometry concept.

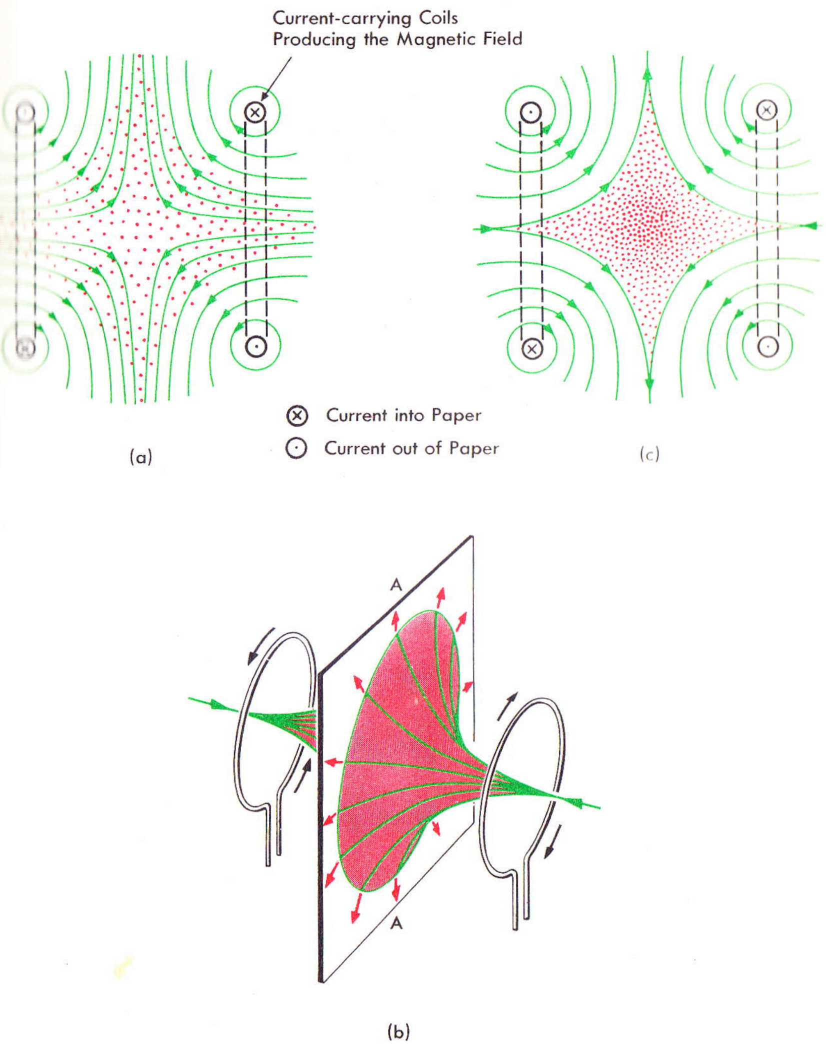

FIG. 14–1. PICKET-FENCE AND CUSPED GEOMETRY. (a) In Picket Fence, the low-density plasma escapes rapidly out between the lines of magnetic force in plane A-A, shown in (b). In the case of a high-density plasma, however, the geometry becomes sharply cusped (c), with a sharp boundary between the plasma and magnetic field.

In the interim, however, encouraging progress had been made toward stabilizing many of the existing experimental projects. Consequently, there seemed to be little justification for continuing further studies with the cusped geometry. For the most part, work on this approach was dropped during 1956, and the NYU group concentrated its attention on a variety of other theoretical problems of interest to the Sherwood effort.

CHAPTER 15

SHOCK-WAVE EXPERIMENTS

Largely because of the difficulties of plasma heating experienced in many of the programs, a number of sites became increasingly interested in the possibility of heating by shocks. The basic principle of shock-heating a plasma is to apply a large pressure in a time short compared with the time required for sound to traverse it. Under these conditions, much of the shock energy results in immediate and irreversible heating of the plasma.

A brief description is given below of the more important efforts made during 1955 to 1958 to shock-heat a plasma to high temperatures.

Work at NRL

In the spring of 1955, a group at the Naval Research Laboratory in Washington approached the Division of Research and expressed interest in participating actively in the Sherwood program. In order that they might gain experience as quickly as possible, it was decided that several members of the group should work at one or another of the Sherwood sites for a period of at least four months and then determine which aspects of the work they wished to undertake. Following this period of indoctrination, the NRL group decided to conduct a fundamental investigation of the properties of high-temperature plasmas, and proposed the use of shock tubes for the production of such plasmas. This proposal was approved, and a jointly financed AEC-NRL program was initiated under the technical direction of W. Faust.

Until the advent of the Sherwood program, probably the highest laboratory temperatures had been produced by shock tubes of one type or another. Values up to 30,000°K had been achieved in some experiments, using more-or-less standard shock-tube techniques.

The temperatures were clearly far too low to be of interest in the Sherwood field. However, as a result of a simple but ingenious modification proposed by A. C. Kolb, it was found possible to increase the plasma temperature substantially. The equipment used in this work consisted simply of a standard T-shaped shock tube, similar to that shown in Fig. 15–1. A sudden electric discharge (produced between the electrodes in the upper arm of the T) would result in the rapid heating and expansion of the gas in that region, thereby forming a shock wave which would travel rapidly down the vertical section, shock-heating the gas as it went.

The innovation incorporated into the apparatus at NRL was to superimpose a strong pulsed magnetic field upon the initial discharge in such a way that the plasma of the discharge was accelerated rapidly down the tube. The magnetic field required for this purpose was attained very simply and expeditiously by bringing one of the electrode leads close to the wall of the discharge tube, as shown in Fig. 15–1. This procedure made it possible to greatly increase the velocity of the shock front. It was, in fact, found that intense shocks of this type could produce temperatures of the order of 500,000°K and higher in the gas through which they passed. Still higher temperatures were achieved by the simple expedient of using an H-shaped tube and firing two shocks against each other. In this way, the ordered motion of each shock along the tube was brought to an abrupt halt upon their collision, and the kinetic energy associated with this motion went into increasing the thermal energy of the plasma.

The early work of the NRL group was concentrated largely on the problem of increasing plasma temperatures as much as possible by these shock techniques and of developing suitable diagnostic methods for determining the actual values obtained. No attempt was made to confine the hot plasma ions once they were produced. As a result, they escaped immediately to the walls of the shock tube and dissipated their energy there within a fraction of a microsecond.

Once plasma temperatures of the order of a million degrees had been successfully achieved, attention was turned, early in 1957, to the problem of keeping the hot plasma away from the walls and of heating it further by magnetic compression. A set of coils was added to the vertical section of the tube; by activating them at the time of the discharge, strong pulsed magnetic fields were produced which compressed and heated the shocked plasma, confining it in a mirror-type configuration in the center of the tube. Fields of several hun-

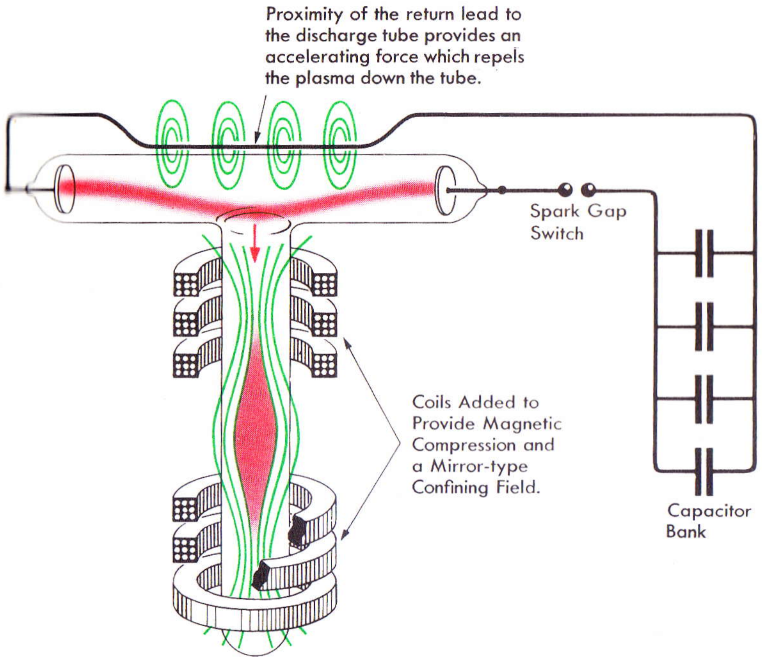
Proximity of the return lead to the discharge tube provides an accelerating force which repels the plasma down the tube.
Spark Gap Switch
Coils Added to Provide Magnetic Compression and a Mirror-type Confining Field.
Capacitor Bank

Fig. 15–1. Shock Tube. A sudden electric discharge between the electrodes in the upper arm of the tube results in a shock wave that travels rapidly down the vertical section. The velocity of the shock may be significantly increased by the magnetic field produced by current in the return lead. A high-temperature plasma is thus formed which may subsequently be trapped in the rising mirror configuration.

dred thousand gauss were built up in the central region for period of the order of 10 microseconds.

In this way, high-temperature, high-β plasmas were produced and studied in detail. Photographs taken with a streak camera permitted observation of the behavior of the plasma during the entire cycle. As of early 1958, there were indications of possible instabilities in the plasma during the period of maximum compression. In addition, high-energy radiation was produced which appeared to be due either to neutrons or to hard x-rays. Careful investigation of both these topics was undertaken.

Work at UCRL

As discussed earlier (pages 68–70), several attempts had been made by S. A. Colgate, in 1954, to ionize and shock-heat a cold gas by a sudden increase in the magnetic field surrounding it (see Fig. 6–2). It was found in those preliminary experiments (known as Collapse), that the process of ionization did not occur sufficiently rapidly to permit a clearly defined shock to be formed. In subsequent work, carried out over a period of several years, a number of modifications were incorporated which permitted the processes of ionization, boundary-layer formation, and shock generation to be accomplished in three successive steps. In the final step, the magnetic field in the discharge chamber was raised very abruptly (in a fraction of a microsecond) from 1000 to 3000 gauss. This procedure permitted a clearly defined shock to be produced, the structure of which could then be studied experimentally and compared with theoretical predictions.

Among other things, Colgate was particularly interested in the behavior of shocks in the limit of no particle collisions. This matter had also been investigated theoretically by H. Grad, M. H. Rose, H. Rubin, and others at NYU. According to theory, a weak shock should, in this limit, result in heating the ions preferentially, whereas a strong shock might be more apt to heat the electrons. A detailed knowledge of shock behavior would clearly be of value in learning how to produce high-temperature plasmas.

Work at Los Alamos

Still another interesting development occurred at Los Alamos in late 1957, involving shock excitation of a plasma, followed by very

rapid and powerful adiabatic compression. In earlier work based on a slightly different approach, the compression had been too slow; scattering collisions permitted plasma particles to escape out the ends of the compression region long before high temperatures had been attained.

To overcome this difficulty, a very simple but effective experimental model, known as Scylla, was built by a group under the guidance of W. C. Elmore. The basic arrangement (similar in some respects to that used in the Collapse experiment described above) consisted simply of two identical single-turn coils mounted coaxially along the discharge tube and connected to a low-inductance capacitor bank. Unlike Collapse, however, strong magnetic fields (40,000 gauss) could be built up in the central region within a period of about one microsecond. The effect of this rapid buildup was first to shock-excite the gas to about 200,000°K and then to heat the resulting plasma still further by powerful adiabatic compression. Radiofrequency excitation was used to provide partial ionization of the gas prior to initiation of the shock.

A rather intense burst of neutrons was found to be emitted just prior to peak compression. As of early 1958, the exact origin of these neutrons had not been determined, but there were plausible reasons for believing that they might be arising from thermonuclear processes.

CHAPTER 16

THE ASTRON PROGRAM

In the meantime, a completely new experimental program made its appearance on the scene. It will be recalled (page 73) that a novel approach for producing thermonuclear reactions had been proposed to the Commission by N. C. Christofilos in 1953. Although the concept was judged to be somewhat crude and incomplete in its original form, Christofilos modified and improved the theory during the next several years, analyzing each aspect in great mathematical detail. As a result of this careful analysis the approach became of increasing interest, and by 1956 it appeared sufficiently promising to warrant Government support. Christofilos, who was then at the Brookhaven Laboratory in New York, was invited to go to Livermore to initiate an experimental effort based on his Astron concept.

Principles of the Astron concept

The key to the Astron approach is a cylindrical sheet of high energy electrons. This electron sheet (E-layer) would be responsible, in principle, both for providing magnetic confinement of the plasma and for heating it to thermonuclear temperatures. The basic features of the concept may be explained in the following way.

By means of external coils, an axial magnetic field would be produced in a large evacuated cylindrical chamber. These coils would be wound in such a way as to produce a small bump in the magnetic field lines at each end of the cylinder, as indicated in Fig. 16–1(a). To this extent there is a slight similarity to the magnetic mirror concept. But here the similarity stops.

Next, a beam of electrons having rather high energies (tens of millions of electron volts) would be injected by some appropriate method into the chamber so as to form a circulating layer of current about the central axis. As this layer is developed, it would produce its own magnetic field, which would modify the field initially present. When the current in the layer reached a high enough value, the net magnetic field in the central region would reverse its direction, producing a configuration similar to that shown in Fig. 16–1(b).

By means of the electron layer, therefore, it should be possible to produce within a cylindrical vessel a magnetic field configuration with lines of force that close completely on themselves, thereby providing an effective method of confining a high-temperature plasma.

At this time, a mixture of deuterium and tritium gas at room temperature would be admitted into the chamber. It would be immediately ionized by the electron layer, and the resultant plasma, now trapped by the magnetic field, would begin to gain energy from successive collisions with the high-energy electrons in the E-layer. Concurrently, there would be a loss of energy from the system, as a result of plasma particles diffusing slowly outward across the closed lines of magnetic field until they eventually reach an "open" line of force and escape. However, it was shown that, in theory, the rate of energy input to the plasma (through collisions with the E-layer) could be made greater than the energy loss from outward diffusion. As a result, it should be possible, in principle, to increase the temperature of the plasma to values of thermonuclear interest.

Experimental program and related studies

One of the major uncertainties in the Astron approach is the stability of the electron layer itself. While computations which have been carried out to date are encouraging in this respect, the matter is so complex that it seemed essential to test the matter experimentally.

Early in 1957, work was begun at UCRL, Livermore, on the first Astron model. The primary purpose of this experiment is to demonstrate whether, with a beam of relatively low-energy electrons (about 1 Mev), it will be possible to establish a stable E-layer, and whether this layer will effectively reverse the magnetic field in the central region.

If successful, the first model will be followed by a larger version, having an E-layer of higher energy, which will test the ability of the layer to confine and heat a plasma in a stable manner. Computations show that if the influx of impurities from the walls can be kept sufficiently low it should be possible to establish a low-density plasma, under steady-state conditions, having a temperature higher than ten million degrees.

Recently, an engineering study was carried out to investigate the capital and operating costs which might be anticipated for a full-scale, power-producing thermonuclear reactor based on the Astron concept. The results of this study, while very preliminary, indicate that such a device might possibly be economically competitive with conventional power sources.

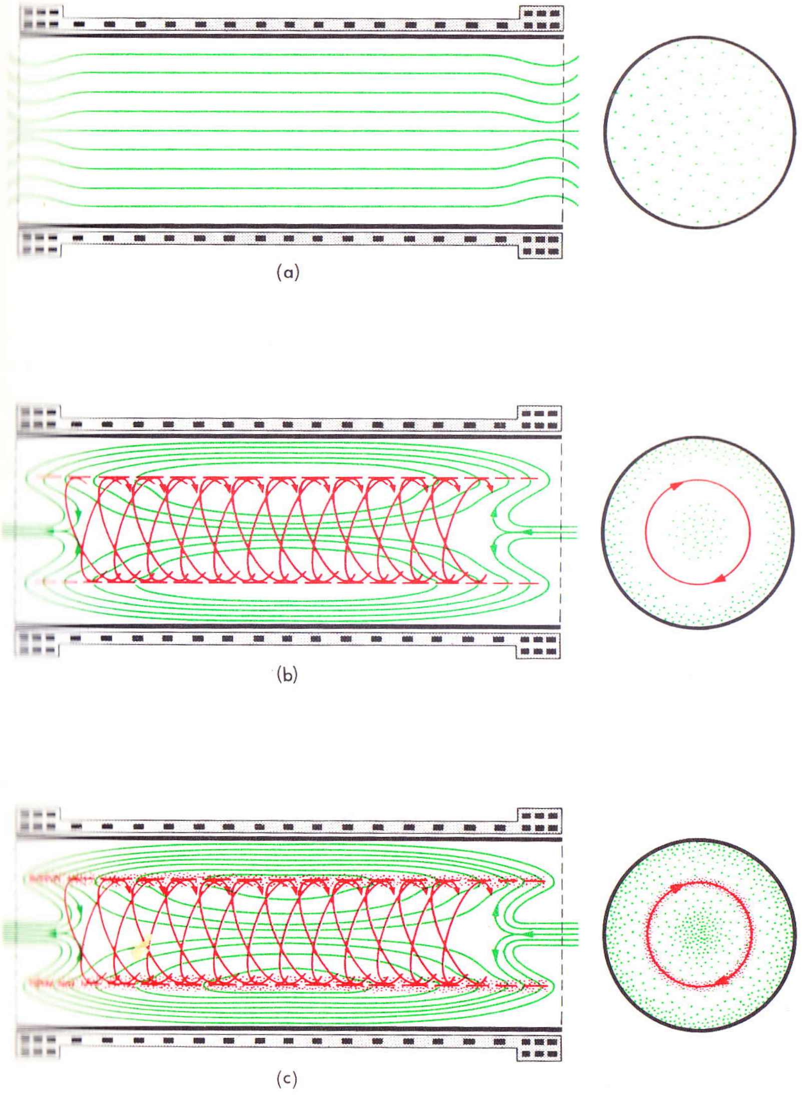

Fig. 16–1. The Astron Machine. (a) An axial magnetic field is produced in an evacuated cylindrical tube. The current-carrying coils are so wound that there is a small bump in the field lines at each end of the cylinder. (b) High-energy electrons are then injected into the cylinder and form a circulating layer of current about the central axis. This current produces a magnetic field which modifies the original field to give a configuration of field lines that close upon themselves. (c) Deuterium or tritium gas at room temperature is then admitted into the chamber and is heated as a result of collisions with the electron layer, producing a high-energy plasma.

CHAPTER 17

DEVELOPMENT OF OTHER PROJECTS (PART II)

In addition to the programs described in the preceding chapter, a number of other developments occurred during the period from 1955 to early 1958. Several of the more significant of these are discussed briefly below.

At the Massachusetts Institute of Technology (MIT), a group was formed during 1955 to study several basic problems of general interest to the Sherwood program, particularly on the subject of high density gas discharges in magnetic fields. This program, carried out under the guidance of J. Wiesner, G. Brown, W. P. Allis, S. C. Brown and others, included experimental and theoretical work on such topics as collision frequencies, ionization frequencies, diffusion and recombination coefficients, and microwave diagnostics.

To assist the Sherwood Steering Committee and the AEC Division of Research in evaluating the relative merits and difficulties of the various Sherwood projects, E. Creutz of the Carnegie Institute of Technology spent nine months during 1955–56 as a full-time consultant-at-large to the program.

A number of contracts were initiated directly between the Division of Research and various industrial groups for developmental work of value to the Sherwood program as a whole. The more significant of these were with:

Westinghouse Electric Corporation for the development of ultra high vacuum technology applicable to large systems.

Gould-National Batteries, Inc., for developmental work on a modified "Kapitza-type" battery, capable of discharging the greater portion of its stored energy in a small fraction of a second.

General Electric Company for work on barium-titanate capacitors suitable for use in fast pinch or other shock experiments.

A project was initiated at the Stevens Institute of Technology, under D. Finkelstein and W. H. Bostick for the study of plasma blobs ("plasmons") formed from spark discharges, and their motion across magnetic fields. This work was a continuation of that carried out earlier at UCRL.

Work was sponsored at the University of Illinois, under P. Coleman, on the development of microwave technology in the millimeter range, for use in plasma diagnostics.

Study projects in the Sherwood field were initiated at the University of Michigan and the University of Indiana.

CHAPTER 18

COORDINATION AND ADMINISTRATION OF THE SHERWOOD PROGRAM (PART II)

FROM 1955 TO EARLY 1958

The major task of the Controlled Thermonuclear Branch of the Research Division was the over-all coordination, direction, and administration of the many projects discussed in the previous chapters. In addition, however, the Branch was involved in numerous other matters of a more general nature, some of which are outlined below.

Industrial participation in the Sherwood program

Up to 1956, nearly all the Sherwood work had been carried out in Commission laboratories and at universities under contract with the Commission. Industry was, however, being increasingly called upon to undertake some task specifically required by one or another of the various laboratories. In many cases this work would be done on a completely unclassified basis, with no need for the industrial group to have access to classified information; there were other cases, however, in which it appeared essential for those engaged in the work to have full knowledge of the over-all program. Several of these latter cases have been discussed: for example, in connection with the preliminary design studies of large-scale stellarator models, the development of special systems of energy storage, and the production of ultra high vacua. Here the work was carried out under contract with the Commission (or directly with one of its Sherwood laboratories), and classified information in this field was provided with the understanding that it would be limited to those requiring it to carry out the task at hand.

With the rapid growth of the Sherwood effort, however, there were increasingly cogent reasons for providing qualified industrial groups with access to Sherwood information, even in the absence of a contract in this field.

Among other considerations, a number of companies already were (or were planning to become) deeply involved in the fission reactor program and were understandably concerned over the possibility of early success in the Sherwood program. It was recognized that before these companies could be expected to make additional investments in the fission field, they had a right to see for themselves what was over the horizon and to make their own judgments of how far away the horizon was.

An equally important consideration was the fact that the Sherwood program was approaching the stage when industrial groups could be expected to participate to a sizable extent in the effort, either with AEC assistance or possibly with their own funds. To encourage this participation, it was clearly essential that qualified companies should be able to gain access to Sherwood information.

Access to Sherwood information

For these reasons, the Commission took action in June, 1956, to make Sherwood information available to those companies or individuals who qualified for classified access permits. To qualify, an applicant had either to be engaged in a substantial effort to develop, design, build, or operate a fission power reactor that was planned for construction, or to possess qualifications demonstrating that he was capable of making a significant contribution to research and development in the controlled thermonuclear field.

In addition to receiving full reports on the progress of the Sherwood work, these groups were also invited to send limited representation to the large classified Sherwood meetings held at various spots throughout the country. The first of these meetings attended by access-permittees was held in February, 1957, in Berkeley, California* and next in February, 1958, in Washington, D. C.

The effect of this access was immediate; a number of firms established their own study projects in the Sherwood field; in addition, several of the larger companies (General Dynamics, General Electric, and Westinghouse) publicly announced that they were initiating experimental work with private funds; still other companies, after reviewing the Sherwood reports, approached the Commission with proposals for undertaking, with AEC assistance, research and development projects of one type or another in the field of controlled fusion.

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* In Berkeley, the meeting was held during the daytime in a movie theater that happened to be showing (for the public in the evening) a double-feature having the titles "Men of Sherwood Forest" and "Top Secret Affair"!

The question of classification

Ever since the inception of the Sherwood program, a great deal of thought had been given to the question of appropriate classification of the effort. The matter was widely and freely discussed among the scientists at the various Sherwood laboratories and at each of the conferences held; it was one of the topics on the agenda at nearly every Steering Committee meeting; it was carefully studied within the Division of Research and the Division of Classification. The pros and cons of the matter were presented for consideration on numerous occasions to the Senior Responsible Reviewers (the advisory group to the Commission on classification matters), to the General Advisory Committee, and to the Commission itself.

As discussed on pages 76–77, the factor chiefly responsible for the rather high classification initially placed on this subject was the recognition that, if successful, the achievement of controlled fusion would provide an intense source of neutrons which could have great military significance from the standpoint of producing fissionable material. The field was in its infancy; no one had sufficient knowledge or experience to judge the magnitude of the hurdles to be overcome or the likelihood of a "break-through" at an early date. At a time when neutrons were still scarce throughout the world, these considerations were not to be taken lightly.

First public statements of the Sherwood program

Prior to the first International Conference on Atomic Energy (held in Geneva during August, 1955), information in the controlled thermonuclear field had been held very closely by all nations involved in the effort. While there had been vague indications that several countries had programs underway, no official statement had been made by any country as to the scope of its effort, the laboratories engaged in the work, or the names of those chiefly responsible.

It was recognized that although the approaching Geneva conference was largely dedicated to the subject of nuclear fission, the topic of fusion might well be raised. To permit the possibility of at least a limited discussion of U. S. activity in this field, the Commission took official action on July 28, 1955, to declassify the fact that the United States was actively engaged in such a program. This information was disclosed a week later at the Geneva Conference in response to the public interest aroused by the opening remarks of H. Bhabha (India), in which he predicted that fusion power would be achieved within twenty years.

A month and a half later, a press conference was held in Washington, D. C., at which time information was released concerning the names of the key people involved in the Sherwood program and the laboratories at which the work was being carried out.

Trend toward declassification

By this time the justification for strict classification in this field was diminishing rapidly. During the period since the initiation of the Sherwood effort, neutrons were becoming much more readily available throughout the world as a result of the rapid development of fission-type reactors. In addition, the complexities of the field of controlled fusion were now seen much more clearly; it was recognized that the path or paths toward eventual success would be long and tortuous, with little chance of finding a major short-cut. Another important factor was the general feeling that, with declassification, progress would be accelerated not only because of the free interchange of information that would result, but also because of the opportunity for additional qualified people (particularly those in academic life) to participate actively and fully in the effort.

Nevertheless, many still had mixed feelings regarding the desirability of extensive declassification, particularly in view of its irreversible nature.

During the spring of 1956, the pros and cons of the classification question were again reviewed by the various groups responsible for this matter. In addition, a special *ad hoc* committee, consisting of L. Spitzer, Jr., E. Teller, J. L. Tuck, and E. Wigner, was convened in Washington on May 23, 1956, to discuss the question with the AEC Commissioners and staff. The strong consensus of all these groups was that no information of military significance had been developed to date or would be likely to develop in the foreseeable future. All things considered, it was judged both appropriate and advantageous to declassify much or all of the work that had been done.

Interchange of information with the United Kingdom

It was, however, recognized that it would be desirable for any declassification action to be carried out multilaterally (preferably by all of the nations engaged in this field), rather than by the United States alone. Considerable thought was, in fact, given to the idea of holding an international conference on the subject, at which all nations engaged in fusion activities would be encouraged to declassify and present the full extent of their work. As a first step toward this goal, it was recommended that steps be taken to seek interchange of fusion information on a classified basis with the United Kingdom, so as to determine both the extent of their progress in this field and their views on the question of classification. On the basis of these recommendations, in June, 1956, the Commission authorized (subject to the concurrence of the British) a complete exchange of information on controlled fusion with the United Kingdom.

Following an interchange of correspondence on this subject between Commission Chairman L. L. Strauss and Sir Edwin Plowden, Chairman of the British Atomic Energy Authority, a meeting was held in New York City early in October between T. H. Johnson, A. S. Bishop, C. L. Marshall (Director of the AEC's Division of Classification) and Sir John Cockcroft, then Director of the Harwell Laboratory in England. At this meeting the groundwork was laid for a rapid and continuing exchange of visits and technical reports between the programs in the two countries. Just a few days later a small group of British scientists attended a Sherwood conference in Los Alamos, where both programs were discussed in detail. A return visit to Harwell was arranged for November, and from then on every major meeting in this field included representation from both countries. The exchange of information thus instigated proved to be fruitful and mutually beneficial in every respect.

As a result of additional discussions between U. S. and U. K. representatives in late 1956, agreement was reached on the features of a somewhat relaxed classification policy relating to information developed in the two programs. A classification guide embodying this joint policy and specifying the areas of classified and unclassified information was adopted by the U. S. Atomic Energy Commission on March 6, 1957.

While this classification guide permitted the release of only the more fundamental and basic aspects of the controlled fusion program in the two countries, it was agreed that further declassification action would be taken jointly in time to permit extensive (if not complete) discussion of this field at the time of the second Geneva Conference, in September, 1958. A sizable fraction of the agenda of this conference was, indeed, allotted to a discussion of the controlled thermonuclear effort.

Public release of information

During this period, a number of public statements and articles in the field of controlled fusion began to make their appearance. In late 1955, general discussions of the subject were presented at an industrial conference in New York by H. D. Smyth (Princeton) and H. Thirring (Austria). This was followed, in May, 1956, by a lecture at Harwell by Soviet Academician I. Kurchatov, who described in detail the results of some of the work which had been carried out in Russia on the pinch effect. Further presentations of a somewhat more general nature were made in the U. S. during the summer and fall of 1956 by E. Teller, R. F. Post, J. L. Tuck, M. B. Gottlieb, E. A. Frieman, A. C. Kolb, W. H. Bostick, and others.

By the end of 1956, scientific interest in this field was rapidly increasing. Stimulated largely by the experimental results disclosed by Kurchatov, scientists in a number of countries had undertaken active research programs in this field, most of them based on the pinch effect. At an international conference in Venice on gaseous electronics (June, 1957), papers were presented by France, Germany, Great Britain, Sweden, the United States, and the U.S.S.R. on various aspects of their theoretical or experimental programs in controlled fusion. Papers were presented by the U. S. team on such subjects as the origin of neutrons observed in the pinch effect and stabilization of the pinch by means of an internal magnetic field. Lively discussions were carried out in a number of languages and, for the first time, the subject began to assume a truly international flavor.

In January, 1958, following further declassification action specifically requested by the British, a major disclosure was made jointly by the United States and the United Kingdom covering nearly all the work then underway in the pinch field. Four months later, in May, 1958, the United States released basic information concerning the stellarator, magnetic mirror, and molecular ion beam concepts.

Changes in personnel

During 1956 and 1957, a number of personnel changes occurred in the direction of the Sherwood program. A. S. Bishop resigned late in 1956 as head of the AEC's Controlled Thermonuclear Branch and was succeeded by A. E. Ruark. Over the following year, the staff of the Branch was enlarged by the addition of H. Roderick, H. S. Morton, and others. During 1957, E. Teller and W. Brobeck resigned from the Sherwood Steering Committee; in their place, H. York was invited to become a member and represent UCRL. Toward the end of the same year, T. H. Johnson resigned from the post of Director of Research and was succeeded by Acting Director P. W. McDaniel.

CHAPTER 19

SUMMARY AND OUTLOOK

Some seven years have passed now since the inception of an experimental effort in the Sherwood field. Over this period, the Atomic Energy Commission program has grown rapidly in magnitude and scope. Beginning with barely a handful of scientists working in temporary wooden laboratories at several sites throughout the country, the effort has approximately doubled in magnitude each year since its inception. A rough indication of this growth, in terms of annual expenditures and scientific man-years, is given in Fig. 19–1. With the rapid expansion in staff and in number of experimental models, extensive new accommodations were required at each of the major sites.

Scope and magnitude of the present Sherwood program (Fig. 19–2)

To summarize the present status of the effort, extensive work in the Sherwood field is now underway at four major laboratories in the United States:

Los Alamos Scientific Laboratory, where a group directed by J. L. Tuck is concentrating its efforts for the most part on the pinch approach. Recently, work has also been initiated on other methods of plasma confinement and heating, involving magnetic mirrors and rotating plasmas.

Princeton University, where a staff of scientists and engineers, supplemented by a group from industry, is working almost wholly on the stellarator concept under the direction of L. Spitzer, Jr.

University of California Radiation Laboratories (UCRL) in Berkeley and Livermore, where, under the general direction of C. M. Van Atta, a rather diversified experimental effort is under way. One group under R. F. Post is engaged in work on the magnetic mirror approach; two separate groups under W. R. Baker and S. A. Colgate are working on the pinch effect; still another, headed by N. C. Christofilos, is pursuing the Astron concept. Rotating plasmas are also being studied.

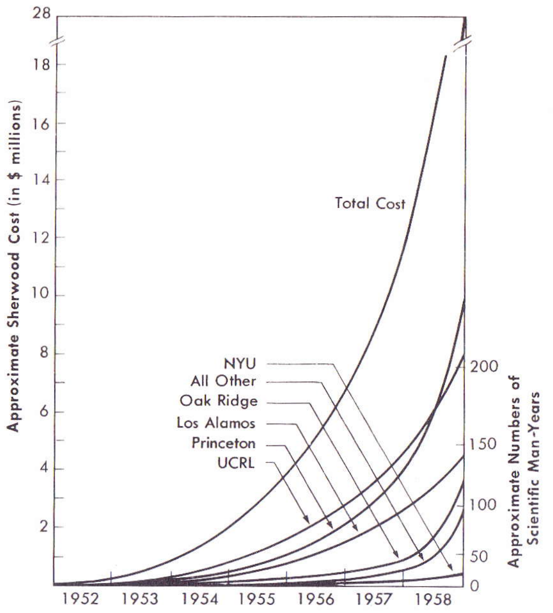


FIG. 19–1. APPROXIMATE SHERWOOD COSTS. This graph shows roughly the annual rate of expenditures at the various Sherwood installations. The scale at the right shows the approximate number of scientific man-years devoted to the program.

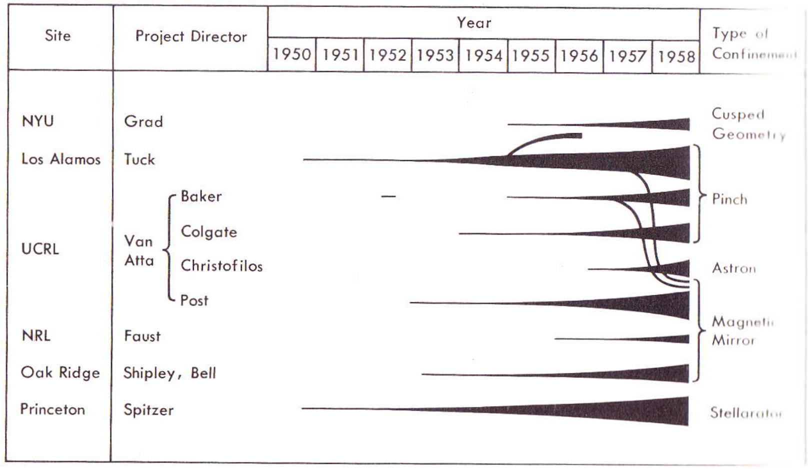


FIG. 19–2. CHRONOLOGY OF THE SHERWOOD PROGRAM, showing methods of plasma confinement in experiments to date.

Oak Ridge National Laboratory (ORNL), where an expanding group under E. D. Shipley and P. R. Bell is investigating the possibility of building up a hot plasma by the injection and dissociation of energetic molecular ions in a magnetic mirror geometry. Work is also being carried out on a number of such related topics as charge exchange, cross sections, and rotating plasmas.

In addition to the above major programs, smaller efforts are underway at a number of other locations, for example:

New York University, where theoretical studies are being carried out under the direction of H. Grad on a number of problems of interest to the Sherwood effort, particularly with regard to stability, shocks, and the general field of magnetohydrodynamics.

Naval Research Laboratory (NRL), where a group under W. Faust is engaged primarily in the problem of shock-heating a plasma, with subsequent magnetic mirror confinement.

Massachusetts Institute of Technology (MIT), where, under the general guidance of J. Wiesner, a variety of problems is being studied, primarily with regard to methods of diagnostics and the general behavior of plasmas in magnetic fields.

Supplementing these programs, a number of supporting projects of a research and developmental nature have been initiated at various other laboratories throughout the country.

The over-all coordination and administration of the entire program is under the direction of A. E. Ruark, head of the Controlled Thermonuclear Branch of the Commission's Division of Research. In these matters, assistance is provided as required by local AEC operations offices. A chart showing the channels of Sherwood responsibility is presented in Fig. 19–3.

Brief summary of the developments to date and the problems being faced

Where then does the program stand at the present time? What have been the major developments up to now, and what are the problems currently being faced? The next few paragraphs attempt to provide, without reference to the laboratories involved, a brief summary of these matters for each of the major approaches.

Pinch approach. Over the past seven years, the pinch approach has gone through a rather complex evolution. The original method of pinch formation and heating—that of applying a low gradient of voltage along the discharge tube—was found to be much too slow to be suitable. Kink instabilities developed that destroyed the pinch long before high enough temperatures could be reached. An intensive effort was accordingly initiated to seek more rapid methods of plasma heating—an effort which culminated in the powerful M-theory method of shock-heating. With this method there was hope that by very rapid contraction of the pinch sheath thermonuclear temperatures could be achieved before instabilities developed. Rapid contractions of this nature required the application of high-voltage gradients, which in turn predicated the use of discharge tubes with insulating walls. Experimental work based on the M-theory concept yielded temperatures of about one million degrees, and neutrons (albeit of dubious thermonuclear origin) were found to be emitted from the plasma itself. Elaborate plans were made to achieve still higher temperatures with larger and improved models.

Late in 1955, however, the picture changed abruptly when it was found theoretically possible to stabilize the pinch completely by the combination of an axial magnetic field within the pinched plasma and a conducting surface at the walls of the discharge tube. For the first time, there was real hope of maintaining a stabilized pinched discharge for periods of thermonuclear interest. Experiments carried out with both straight and toroidal discharge tubes gave clear evidence of stability for brief periods at plasma temperatures estimated as high as five million degrees.

This technique of stabilization has proved, however, to be a mixed blessing; its great potential advantages have been somewhat offset by several new and severe complications. Among other difficulties, the presence of the axial stabilizing field greatly limits the effectiveness of the M-theory method of heating, and other processes are being sought for raising the plasma to thermonuclear temperatures.

In principle, the interdiffusion of the axial stabilizing field with the circumferential pinch field should provide an adequate heating mechanism, provided the energy losses from the plasma are limited to bremsstrahlung. Recent experiments have indicated, however, that energy is being rapidly lost to the walls of the discharge tube by other processes, presumably of an instability nature. While there is hope that the various difficulties encountered in the B_Z-stabilized

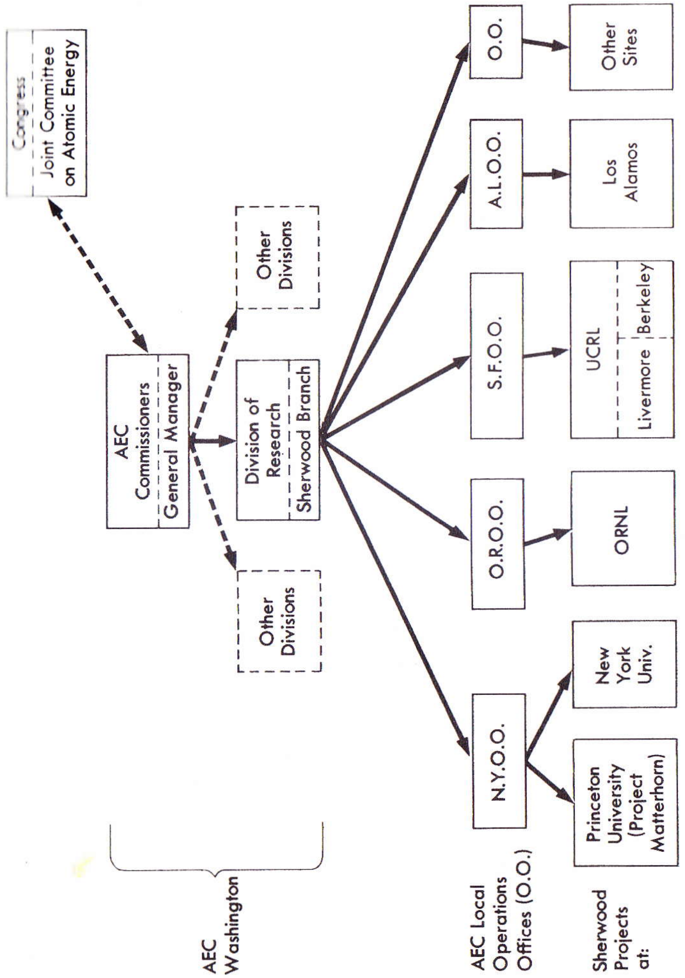


Fig. 19-3. Channels of Sherwood Responsibility.

pinch approach can be overcome, other possible methods of achieving stabilization (or quasi-stabilization) are being explored.

Stellarator approach. The stellarator concept, too, has undergone interesting modifications over the past seven-year period. In the concept, in which the plasma is confined in an endless tube by means of an externally imposed axial magnetic field, the configuration originally proposed was that of a figure 8. This shape was chosen to provide a rotation of the lines of force as they traverse the tube, thereby satisfying one of the necessary conditions of plasma confinement. A number of useful experimental models were built using this configuration, and various methods of plasma heating were developed and tested.

Later, as a result of concern over the problem of interchange instability, theoretical studies led to the development of a simpler geometrical system possessing inherent stability; namely, a toroidal discharge tube in which the rotation of the lines of force is achieved by adding a set of helical conductors wound around the outside of the tube. The addition of these windings provides not only the rotational transform necessary for confinement but also the shear fields required to stabilize the system. According to theory, however, the maximum value of the pressure ratio β that can be achieved under stable operating conditions is limited by the amount of shear that can be produced with the stabilizing windings. In turn, the limitation on β affects the long-term outlook for developing economic power from a full-scale stellarator. While the maximum value of β that can theoretically be attained with these shear fields is lower than might be desired, it is nevertheless high enough to make the stellarator concept of continuing practical interest.

There is, moreover, still much to be learned about the question of instability. While there is sound theoretical reason to believe in interchange instabilities, it must be stated that as yet there is no experimental evidence of their existence, even under conditions when they would be theoretically expected. The Model C stellarator, now under design and construction, should be of great value in this respect. Designed as a large but flexible experimental facility capable of achieving temperatures of 100 million degrees, it should yield valuable information concerning the capabilities and limitations of a full-scale stellarator. In addition, it is hoped that later modifications will permit coming to grips with the interchange instability problems and determining the effectiveness of the proposed methods of stabilization.

In the meantime, much experimental data is being acquired with the smaller B-size stellarator models. Temperatures of about one million degrees have already been achieved with existing methods of plasma heating, and tests are under way on powerful techniques which should be capable of heating the plasma rapidly to much higher temperatures. Numerous experimental difficulties continue to plague the progress of the work; there is, however, reason to believe that these difficulties can and will be overcome in time.

Magnetic mirror approach. In the magnetic mirror approach, confinement is provided in a straight cylindrical tube by means of an externally imposed axial magnetic field with mirrors at the two ends. Plasma injected into the chamber is trapped and heated by the process of adiabatic compression. The major problem from the outset has been that of developing satisfactory ion sources capable of injecting copious quantities of moderate energy ions into the system. In parallel with an intensive effort to develop such sources, much work has been carried out with relatively small experimental models using available low-energy injectors. In spite of difficulties caused by impurities and neutral particles, this work has confirmed the theory of trapping and heating a plasma in time-rising magnetic fields. Ion temperatures of more than 5 million degrees (and electron temperatures substantially higher) have been reported from these experiments.

Recently, improved sources having ion energies of several kilovolts have become available, thereby offering the hope of achieving much higher plasma temperatures by this method. If the remaining difficulties can be overcome (such as adequate neutralization of the beam and a reduction of the ratio of neutrals to ions), there will be justification for scaling up to larger discharge chambers, in which the trapping efficiency would be much greater.

In spite of earlier concern that the magnetic mirror approach might be unstable, no evidence of instability has yet been found. Several plausible reasons have been advanced to explain this discrepancy with the (admittedly approximate) theoretical predictions; it is, however, too early to know whether the system will continue to be stable at higher temperatures and densities, or whether special modifications will be necessary to provide stability.

Still another source of concern is the rate of loss of particles out through the mirrors. While the theoretical treatment of this problem is difficult, it is now evident that the recovery or reduction of energy escaping by this route will be an important factor in any practical full-scale mirror machine.

As one possible means of alleviating this difficulty, one may point to the recent work on rotating plasmas. Applied to the magnetic mirror concept, it is possible that mass rotation of the plasma may substantially reduce the rate of loss of energetic particles through the mirrors.

Molecular ion injection approach. Another approach to the problem of forming a high-temperature plasma is that of molecular ion injection. In experiments now in progress, molecular deuterium ions having energies of hundreds of kilovolts are injected transversely into a static magnetic field and dissociated by a special carbon arc. The immediate goal is to build up a high concentration of energetic atomic ions and to confine them long enough in mirror geometry for their motion to randomize, with consequent formation of a truly thermalized plasma at thermonuclear temperatures. Here the major problem is to attain high enough intensity of injected ions and low enough background of neutral particles so that "burnout" can occur. Recent results have been encouraging, and a strenuous effort is being made to reach this goal.

For reasons of experimental convenience, present studies are being performed in a magnetic mirror configuration, but it has been shown that this method of plasma ignition, if successful, should also be applicable to closed geometries such as the stellarator.

Other approaches. Still other approaches have been or are being explored, but are in a somewhat earlier stage of development than those given above. In one of the more promising, the Astron approach, the immediate task is to establish a layer of circulating high energy electrons. If this E-layer can be shown to be stable, it should provide an important new method of plasma confinement and heating.

Over-all status and outlook for success

It is clear that the end is not yet in sight. There is still a long row to hoe before the final goal will be reached.

Nevertheless, in looking back over this short seven-year period, it is also clear that very substantial progress has been made to date. A number of completely different methods have been proposed for confining a plasma and heating it to thermonuclear temperatures. Extensive experimental work has been carried out on the more promising of these approaches, and numerous operating models have amply confirmed their basic principles of operation. Already, several laboratories have reported achieving plasma temperatures in excess of a million degrees—more than thirty times higher than the maximum attained before the Sherwood program was begun. More important, the groundwork, for the most part, has already been laid for moving on to still higher temperatures.

These various approaches differ rather markedly not only in their methods of confinement, but (as shown in Fig. 19–4) in the way in

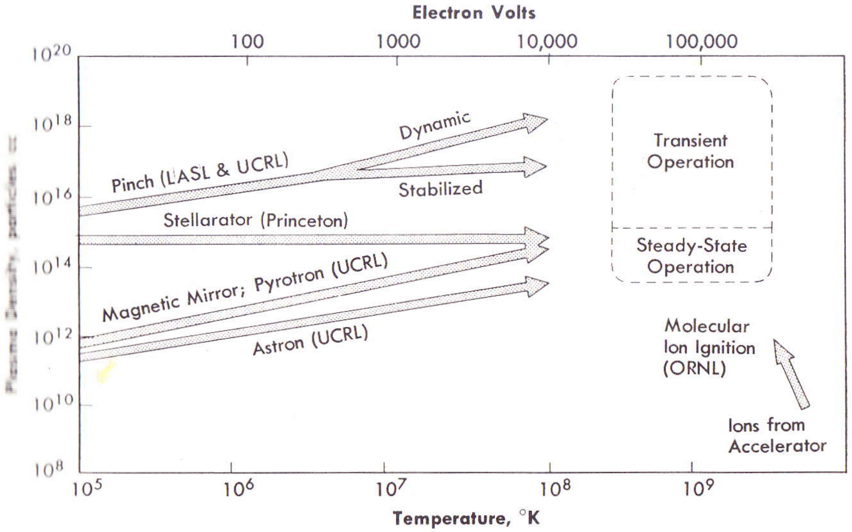


FIG. 19–4. VARIOUS APPROACHES. This chart shows only the lines of approach and is not an indication of the magnitude of the projects.

which they approach thermonuclear conditions. Each has its special advantages which make it particularly fascinating for its proponents. None is without its difficulties.

Fortunately, the field is new and still fluid. New ideas can, almost overnight, cause a major shift in emphasis and outlook. A case in point is the stabilization of the pinch; another is the use of a carbon arc to dissociate molecular deuterium ions. Clearly, it is still too early to favor one approach over the others, and none should be discounted at this stage.

One of the more encouraging developments is the rapid progress made in the past several years in understanding the behavior of plasmas in magnetic fields. This progress has been due in part to extensive theoretical studies and in part to improved techniques of diagnostics which permit detailed experimental analysis of plasma behavior. Even such complex "cooperative phenomena" as instabilities are now beginning to be understood, and theoretical methods of stabilization can be applied to experimental models with some degree of confidence.

Over the next few years, new and improved models now under design or construction will be coming into operation. Barring unforeseen difficulties, it should be possible with these models to push to still higher values of temperatures and densities than those achieved to date—values approaching those of practical interest.

Because of the enormity of the problems involved, progress may be expected to be slow and halting. Up to the time of this writing, however, no basic obstacle has been discovered which would prevent the attainment of the final goal. With ingenuity, hard work, and a sprinkling of good luck, it even seems reasonable to hope that a full scale power-producing thermonuclear device may be built within the next decade or two.

Whether the process of controlled fusion can ever be made economically competitive with such other sources of energy as coal, oil, and fission reactors is anyone's guess. It is, however, reasonable to expect that, if successful, this new source of energy will not displace the others, but rather will supplement them during this era of rapidly expanding power requirements.

Unquestionably, it is a program of rare importance, offering mankind for the first time in history the prospect of an essentially unlimited source of energy. Over the shorter term future, the technical problems still to be solved present a stimulating challenge to trained people the world over. With several countries already actively engaged in the field and others ready to join their ranks, it is to be hoped that there will result a fruitful exchange of ideas and technology which will speed the attainment of the final goal.

APPENDIX I

SEVERAL FUNDAMENTAL TOPICS OF PHYSICS

Elementary particles

The three most important building blocks of matter are the electron, the proton, and the neutron. The electron has a negative charge e of 4.80×10^{-10} electrostatic unit (equivalent to 1.60×10^{-19} coulomb) and a mass m of 9.11×10^{-28} gram. Expressed in units of electron charge and mass, the values for all three particles may then be written:

	Charge, in units of e	Mass, in units of m
Electron	−1	1
Proton	+1	1836
Neutron	0	1845

Structure of the atom

According to present views, each atom is composed of a small heavy core, or nucleus, about which revolve a number of electrons, much in the way that the planets revolve about the sun. The nucleus itself has a diameter of about 10^{-12} centimeter, and is believed to be a complex structure, consisting only of neutrons and protons. It thus possesses an integral positive charge equal to the number of protons it contains. In any neutral atom, the positive charge due to the protons in the nucleus is counterbalanced by the negative charge of an equal number of external electrons that encircle the nucleus in definitely prescribed orbits of roughly 10^{-8} centimeter diameter. Thus the atom as a whole has zero net charge.

In turn, it is the number of external electrons that determines the chemical properties of the atom and distinguishes the various chemical elements. The simplest element is hydrogen, which possesses only one electron encircling a nucleus with but one proton. The next simplest element, with two external electrons, is helium; then comes lithium, with three electrons, etc. The most complex naturally occurring element is uranium, with 92 electrons encircling its nucleus.

We have seen that the number of protons is identical to the number of external electrons. There is, however, some flexibility in the number of neutrons which may occur in any nucleus, and several different species of the same element may exist. These different species, or *isotopes*, are chemically identical; because of the different nuclear structure, however, their nuclear properties may be different.

The number of protons in the nucleus (and hence the nuclear charge, measured in terms of the unit charge) is usually designated by the symbol Z, and is called the *atomic number*.

The total number of nucleons in the nucleus (i.e., the sum of the number of protons Z and the number of neutrons N) is called the *mass number*, and is designated by the symbol A. It is a whole number approximately equal to the mass of the nucleus, when measured in units of the proton mass.

The table on page 174 presents values of A, Z, and N for several nuclei of interest.

Binding energies

If a nucleus is bound together in a stable way, then a certain amount of energy, the *binding energy* for that nucleus, is required to break it up into its component nucleons. Conversely, when a set of individual nucleons join together to form a stable nucleus, energy is released. This energy arises from the fact that the mass of the product nucleus is less than the total of the masses of the component nucleons, and the difference in mass is converted into its equivalent form, energy. The relationship between mass M and energy E is given by the Einstein equation

$$E = Mc^2,$$

where c is the velocity of light.

The binding energy, B, is thus the energy equivalent of the difference between the total of the masses of the component particles and the mass of the bound nucleus; i.e., it is the energy equivalent of

$$(ZM_p + NM_n) - M,$$

where M_p and M_n are the proton and neutron masses, respectively, and M is the true mass of the bound nucleus.

List of Several Elements and Their Isotopes

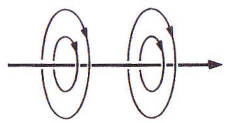
Element			Characteristics of its nucleus				
Name	No. of electrons	Name given to isotope	Name given to nucleus	Symbol	No. of protons, Z	No. of neutrons, N	Mass number, A
Hydrogen	1	Hydrogen	Proton	H^1 (or p)	1	0	1
		Deuterium	Deuteron	H^2 (or D)	1	1	2
		Tritium	Triton	H^3 (or T)	1	2	3
Helium	2	Helium-3	Helium-3 nucleus	He^3	2	1	3
		Helium-4	Helium-4 nucleus	He^4	2	2	4
Lithium	3	Lithium-6	Lithium-6 nucleus	Li^6	3	3	6
		Lithium-7	Lithium-7 nucleus	Li^7	3	4	7
etc. ↓	etc. ↓	etc. ↓	etc. ↓	etc. ↓	etc. ↓	etc. ↓	etc. ↓
Uranium	92	Uranium-235	Uranium-235 nucleus	U^{235}	92	143	235
		Uranium-238	Uranium-238 nucleus	U^{238}	92	146	238

A quantity of somewhat greater interest is the binding energy per nucleon, B/A. A study of this quantity shows that the most tightly bound nuclei are those lying roughly in the center of the periodic table, having mass numbers from, say, 40 to 100. Nuclei at the lower and upper ends of the periodic table are in general much less tightly bound. As a result, energy may be released either by breaking very heavy nuclei into smaller fragments or by combining very light nuclei to form heavier ones. The former is the process of *fission*, the latter the process of *fusion*.

Magnetic fields

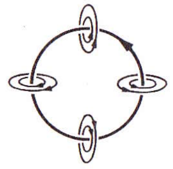
Any flow of charge produces an associated magnetic field, whether the current results from electron flow in a wire or by the motion of charged particles in a gas. Suppose, for example, that a current I exists in a straight line along an axis. Then an encircling magnetic field will be produced, as shown in figure (a). At a distance r from the axis, the strength of this field is given by the relationship

$$B = \frac{2I}{r}.$$

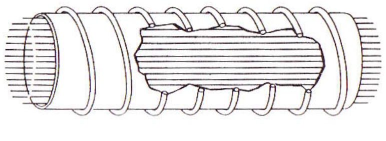

(a)

[If I is in abamperes (defined as 10 amperes) and r is in centimeters, then the field strength B is given in gauss.]

In a similar way, if a flow of charge passes around in a ring, it produces encircling lines of force as shown in figure (b). At the center of the ring, the magnetic field strength into the paper is given by $B = 2\pi I/a$, where a is the radius of the ring.

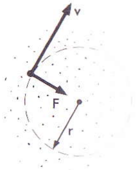

(b)

For the case of a reasonably uniform (homogeneous) magnetic field produced inside a long helical winding at the center of a coil [figure (c)], the field strength B is given by $B = 4\pi nI$, where n = number of turns per unit length.


(c)

Force on a moving charged particle in a magnetic field

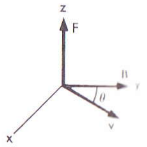
If a charged particle moves in a magnetic field, it will experience a force at right angles both to the direction of the magnetic field lines and to the instantaneous direction of motion of the particle. Suppose, for example, that a magnetic field of strength B is established in a direction perpendicular to the plane of this page, with lines of force out of the paper, as indicated by the dots in figure (d). If a positively charged particle is moving with a velocity v in the plane of the paper, it will experience a force F at right angles which will tend to bend it into a circular path of radius r. The magnitude of the force is given by the relationship $F = Bev$. If B is expressed in gauss, e in esu, and v in centimeters per second, then F is in dynes. For a negatively charged particle the direction of the force would be reversed.



(d)

The inward magnetic force is counterbalanced by the outward centripetal force mv^2/r. By equating these forces, the radius r is found to be mv/Be.

More generally, if v and B lie at some angle θ to each other [figure (e)] then the force F is in a direction perpendicular to the plane passing through B and v; its magnitude is given by $F = Bev \sin \theta$. Thus if v lies in the same direction as the magnetic field, the particle will experience no deflecting force whatsoever.



(e)

Diamagnetic effect of charged particles moving in a magnetic field

It should be noted that the motion of a charged particle in a magnetic field creates its own field, which is always in opposition to that originally present. In a similar way, if an assembly of charged particles (e.g., a plasma) is confined by an externally applied magnetic field, their motion will reduce the net magnetic field strength within the plasma itself. If the density and velocity of the particles are high enough, this "diamagnetic effect" can reduce the internal field to zero. In these circumstances, the particles will move in straight lines within the plasma, and be turned back by the magnetic field at its edge.

APPENDIX II

LOW-TEMPERATURE FUSION

One of the requirements of the controlled thermonuclear program is the achievement of exceedingly high temperatures. As pointed out in Chapter 1, the necessity for such temperatures arises from the fact that the interacting deuterons are positively charged and hence tend to repel one another strongly. High kinetic energies (corresponding to high temperatures) are required so that the deuterons may come sufficiently close to one another to permit fusion.

If, however, the charge of one of the interacting particles could be effectively neutralized, the need for high temperature would be obviated.* A beautiful demonstration of this fact was provided by the work of Alvarez, Bradner, and others at the University of California at Berkeley, who showed experimentally that fusion reactions can be produced at low temperatures with the aid of mu-mesons.

Mesons are a set of unstable particles, and may be produced by bombarding a suitable target with high-energy particles from an accelerator (e.g., with protons having energies of 300 Mev or greater). Of the various types of mesons produced in this way, the negatively charged pi-meson has a mass approximately 273 times that of the electron, has a half-life in free space of the order of 10^{-8} second, and decays into a negative mu-meson (plus a neutrino). The negative mu-meson has a mass of 212 electron masses, a half-life in free space of 2×10^{-6} second, and decays into an electron (plus two neutrinos).

If, however, a negative mu-meson is brought to rest in an atmosphere, say, of deuterium, it will form what is known as a "mesic deuterium atom," i.e., a deuterium atom in which the atomic electron is replaced by the meson. It thus constitutes an electrically neutral system composed of a deuteron encircled by a mu-meson. Since, however, the mu-meson has a mass several hundred times greater than that of the electron, its lowest energy orbit lies closer to the deuteron by the same factor. Because of the neutrality of this tiny system, it can now approach another deuteron very closely without experiencing a force of repulsion, and can form a mesic molecular ion, i.e., a system of two deuterons bound very closely together by the meson which encircles them both.* The deuterons would in this way be bound sufficiently close together that they would have an appreciable chance of undergoing fusion, with consequent release of energy in the form of kinetic energy of the reaction products. The meson would be ejected unscathed in the process; it would then be free to form other mesic atoms and to catalyze other fusion reactions.

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*For similar reasons, high temperatures are not required in the fission reaction. Because of its lack of charge, a neutron, even when moving very slowly, can easily penetrate a U^{235} or plutonium nucleus and cause it to undergo fission.

Unfortunately, as has been mentioned, the mu-meson has a very limited lifetime (several millionths of a second, or even less if, as is likely to happen, it is captured by and interacts with one of the helium nuclei produced in the fusion reaction). Thus even under optimum conditions, a mu-meson has time to catalyze only a few fusion reactions during its lifetime, and the total energy released is only a small fraction of that required to produce the meson in the first place. As a result, mu-meson fusion, while of great scientific interest, does not appear to be a practical means of releasing nuclear energy.

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* The usual molecular deuterium ion consists of two deuterons loosely bound together by an encircling electron. In the mesic molecular ion, however, the deuterons are much more closely bound together because of the greater mass of the meson.

APPENDIX III

THERMONUCLEAR REACTIONS IN THE SUN AND OTHER STARS

It is now widely accepted that among the thermonuclear reactions responsible for energy release in the sun and other stars, one of the most important is the formation of a He^4 nucleus (and two positrons) from four protons. There are two different ways in which such a fusion reaction is believed to occur: the first is the so-called carbon cycle proposed independently by H. Bethe and von Weizacker; the second is known as the proton-proton chain.

In the carbon cycle, the suggested sequence of fusion events is the following, where p = proton (hydrogen nucleus), C = carbon nucleus, N = nitrogen nucleus, O = oxygen nucleus, He = helium nucleus, e^+ = positron (i.e., a positive electron):

$$\begin{aligned}
p + C^{12} &\longrightarrow N^{13} + \text{energy} \\
N^{13} &\longrightarrow C^{13} + e^+ \\
p + C^{13} &\longrightarrow N^{14} + \text{energy} \\
p + N^{14} &\longrightarrow O^{15} + \text{energy} \\
O^{15} &\longrightarrow N^{15} + e^+ \\
p + N^{15} &\longrightarrow C^{12} + He^4
\end{aligned}$$

or, in total, $4\,p \longrightarrow He^4 + 2\,e^+ + \text{energy (26.7 Mev)}$.

In the proton-proton chain, the sequence of reactions is believed to be as follows, where D represents a deuteron:

$$\begin{aligned}
p + p &\longrightarrow D + e^+ + \text{energy} \\
D + p &\longrightarrow He^3 + \text{energy.}
\end{aligned}$$

The He^3 nucleus now interacts with another He^3 nucleus, produced from an identical set of reactions, thereby yielding

$$He^3 + He^3 \rightarrow He^4 + 2\,p + \text{energy}$$

or, in total,

$$4\,p \rightarrow He^4 + 2\,e^+ + \text{energy (26.7 Mev).}$$

In stars having temperatures of about 20 million degrees (as does the sun), the carbon cycle and the proton-proton chain processes occur with roughly equal probability. At lower temperatures, the proton-proton chain is of greater importance, while at higher temperatures the carbon cycle predominates.

In stars, forces of gravitation prevent the escape of charged particles from the hot plasma. Because of the enormous masses of such bodies, this method of confinement is extremely effective, and hence there is no necessity for the thermonuclear reactions to occur rapidly. Both the above stellar processes do, in fact, proceed at extremely slow rates—rates far too slow to permit their practical use in controlled thermonuclear reactions here on Earth. For laboratory experiments in the field of controlled fusion, it is necessary to select, as fuel, nuclei which interact more readily. The most promising of these nuclei are those discussed in the text, namely, deuterium and tritium.

APPENDIX IV

UNPROMISING APPROACHES

One of the intriguing pastimes in the Sherwood field is thinking up new and feasible approaches to the goal of fusion power. Those who have tried it will vouch that it is not an easy task. Of the numerous suggestions advanced over the years, many have been ingenious. The great majority, however, have fallen far short of meeting the basic requirements of a practical fusion device (as outlined in Chapter I). By way of illustration, we list below several approaches suggested perennially but which for one reason or another do not appear to be promising.

Bombardment of a target by high-energy ions

Historically, fusion reactions between deuterium ions were first produced in the laboratory in the late 1930's by bombarding a solid deuterium compound with high-energy deuterons. For a number of reasons, however, this approach is not suitable for a practical fusion device. The principal difficulty is that the impinging particles fritter away almost all their energy in useless ionization of the target atoms. As a result, only a very tiny percentage succeed in colliding with target nuclei with sufficient energy to undergo fusion. The energy yield from these few reactions falls far short of compensating for the energy input required to produce the beam initially.

Bombardment of a gaseous discharge by high-energy ions

Substitution of a gaseous discharge for a solid target improves the picture somewhat, but not enough to make this approach of practical interest. The major difficulty is that the temperature of the electrons in a gaseous discharge is rather low, and the impinging ion beam will dissipate its energy rapidly through collisions with these particles. Since there is no plasma confinement, the energy thus transferred to the electrons is immediately dumped at the walls of the discharge chamber, and the temperature of the discharge remains the same as before.

Colliding ion beams

One way of eliminating the above difficulties is to direct two beams of energetic deuterium ions against each other. This approach fails, however, in at least two respects. In the first place, as mentioned in Chapter 1, the probability of elastic scattering between two ions far exceeds the probability of a fusion reaction. Thus, the ions would, for the most part, be deflected out of the beam long before they undergo fusion. A second and still more devastating consideration is the fact that even with the most optimistic beam intensities, the density of ions in the intersecting beams is many thousands of times too low to yield power densities of practical interest.

Exploding wires

If a high current surges through a fine wire, the wire will explode, thereby releasing a large amount of energy suddenly to the surrounding gas. It is often suggested that thermonuclear temperatures might possibly be achieved by this method, but there are several weaknesses to this approach. The first is that the ions would be heated rather slowly in this process: the electrons would be heated first and then transfer energy to ions through collision. A second difficulty is that the vaporized wire would introduce large amounts of high-Z impurities in the gas, thereby greatly increasing the rate of energy loss by radiation.

APPENDIX V

GLOSSARY OF TERMS

Adiabatic compression	A compression (of a plasma, say) which is not accompanied by the gain or loss of heat from the outside.
Arc	An electric discharge between two electrodes.
Atomic number (Z-value)	A number corresponding to the number of protons in the nucleus (or, in a neutral atom, to the number of external electrons). It is thus an integer expressing the nuclear charge in units of the electronic charge e.
β-value	A pressure ratio; specifically, the ratio of the outward pressure exerted by the plasma to the inward pressure the magnetic confining field is capable of exerting.
Bremsstrahlung	The radiation emitted as a result of the deflection (e.g., through collisions) of rapidly moving charged particles.
Burnout	A term applied to the rapid reduction in the density of neutral particles in a discharge, as a result of their being ionized more rapidly than they are formed.
Capacitor	A device capable of storing electrical energy. Also called a condenser.
Center of curvature (of a particle)	The center about which the particle is rotating.
Charge exchange	The transfer of charge between two bodies, resulting from collision with each other (e.g., the collisional transfer of an electron from a neutral atom to a singly charged positive ion, the latter becoming neutral and the former charged).

Condenser	See capacitor.
Cooperative phenomena	The motion of interacting particles acting collectively, rather than individually (e.g., plasma oscillations, turbulence, instabilities of one type or another).
Coulomb force	The force of repulsion (or attraction) exerted by one electrically charged body upon another.
Critical temperature	The temperature at which the energy generated in a plasma through the fusion process just equals the energy radiated away through the process of bremsstrahlung.
Cross section (for a given event)	A quantity proportional to the probability that such an event will occur per unit time.
Cyclotron frequency	The frequency of natural rotation of a charged particle in a magnetic field.
Degenerate configuration	In the sense used here, a configuration in which the magnetic lines of force close exactly on themselves after passing once around the configuration.
Degenerate system	As used here, a system in which the lines of magnetic field close exactly upon themselves after a single transit of the tube.
Deuterium atom	An isotope of the hydrogen atom with one proton and one neutron in its nucleus, and a single orbital electron.
Deuteron	The nucleus of a deuterium atom.
Diagnostics	The procedure of determining (diagnosing) exactly what is happening in an experiment.

Diffusion	The interpenetration of one substance into another as a result of thermal motion of the individual particles (e.g., the diffusion of a plasma across a magnetic field as a result of collisions).
Direct conversion	The transformation of energy released in the fusion process directly into electrical power, without the necessity for an intermediate heat cycle.
Doppler broadening	The broadening of a spectral line as a result of the motion of the emitting atoms toward or away from the detecting equipment. The magnitude of the broadening can be used to calculate the temperature of the emitting gas.
Electric voltage gradient	The change in voltage per unit length (when measured in the direction of maximum change); equivalent to electric field.
Electron volt, ev	A unit of energy, equal to the energy acquired by a singly charged particle in passing through a potential difference of one volt. 1 ev $= 1.60 \times 10^{-12}$ erg.
Field strength, electric	A measure of the intensity of the electric field, or of the force on a unit charged particle placed in this field.
Field strength, magnetic	A measure of the intensity of the magnetic field, or of the density of the magnetic flux.
Fission	The splitting of a nucleus (such as U^{235}) into two more-or-less equal fragments (fission products), with an associated release of energy. In the process, several neutrons are also emitted.
Fusion	The binding together or "fusing" of certain very light nuclei to form heavier or more stable nuclei. Energy is released in the process.

Gauss	A unit of magnetic field strength (i.e., of magnetic flux density).
Gradient (of electric voltage)	See electric voltage gradient.
Homogeneous magnetic field	A magnetic field of uniform strength.
Hydrodynamics	The science dealing with the action and motion of fluids.
Hydromagnetics	See magnetohydrodynamics.
Ignition temperature	The temperature at which the power produced in the plasma from thermonuclear reactions is equal to that radiated away by bremsstrahlung.
Image converter	A camera which, as a result of an internal electronic image system, is capable of taking photographs using very short (and accurately predetermined) exposure times.
Image currents	Currents induced in one conductor (e.g., the metal walls of a discharge tube) resulting from changes in current in another nearby conductor (e.g., the plasma inside the tube).
Inductance	The impedance offered by an electrical circuit to any change in current.
Interchange instability	The name given to the type of instability in which the plasma interchanges position with the magnetic field. Also called a "flute-type" instability, since flutes would be expected to develop on the interface between the plasma and the magnetic field.
Ion	An atom (or a molecularly bound group of atoms) which have become charged as a result of gaining or losing planetary electrons. A completely ionized atom is one stripped of all its electrons.
Ion source	A device capable of emitting ions.

Isotope	One of several species of the same element, possessing different numbers of neutrons (but the same number of protons) in their nuclei.
Joule	A unit of energy corresponding to a watt-second, or to 10^7 ergs.
Joule heating	See ohmic heating.
Kelvin scale	The scale of absolute temperature, in which the zero is approximately −273°C.
Kruskal limit	A value of current which, if exceeded, should theoretically result in instabilities in the stellarator.
Magnetic confinement	The ability of a magnetic field to prevent the escape of the charged particles of a plasma.
Magnetic pressure	The pressure a magnetic field is capable of exerting upon a plasma.
Magnetic pumping	A term given to a type of plasma heating in which the plasma is successively compressed and expanded by means of a rapidly fluctuating external magnetic field.
Magnetohydrodynamics	The science dealing with the motion of fluids interacting with a magnetic field. Also called hydromagnetics.
Mean free path (for a given event)	The distance a particle will travel, on the average, before undergoing such an event.
Microsecond	One-millionth of a second (i.e., 10^{-6} second).
Millisecond	One-thousandth of a second (i.e., 10^{-3} second).
Neutralized plasma	A plasma with no net charge.
Nonhomogeneous magnetic field	A magnetic field which is not uniform in strength over a given region of space.
Nucleon	A nuclear particle, i.e., a neutron or a proton.

Ohmic heating	Often called Joule heating. The heating which results from the resistance the medium offers to the flow of electric charge.
Periodic table	A table of the chemical elements.
Plasma	An assembly of ions and electrons.
Radius of curvature	The distance from a particle to its center of curvature.
Rotational transform	A magnetic field configuration is said to possess rotational transform if the lines of force, after one circuit around the configuration, do not close exactly on themselves, but are rotated through some angle about the so-called magnetic axis.
"Runaway" electrons	As the energy of an electron increases, the probability of its being scattered (and hence of losing part of its kinetic energy) decreases. Thus, under the influence of an applied unidirectional field, the faster electrons will gain energy at a higher rate than the slower electrons, and they eventually "run away" in energy from the other particles.
Scattering	The deflection of one particle as a result of collision with another. Elastic scattering is scattering in which the total kinetic energy is unchanged.
Shear fields	In the sense used here, magnetic fields that rotate in direction as one moves transverse to the field; e.g., in the stellarator tube, magnetic fields that increase in pitch with distance from the axis.
Shock-heating	The heating produced by the impact of a shock wave.
Shock tube	A tube designed specifically to produce shock waves.

Shock wave	The wave produced (e.g., in a gas) as a result of a sudden violent disturbance. To produce a shock wave in a given region, the disturbance must take place in a time short compared with the time required for sound waves to traverse the region.
Smear camera	See streak camera.
Spectroscopy	The science of analysis of light or other type of radiation, using instruments known as spectroscopes and spectrometers.
Stable confinement	As used here, the ability of a magnetic field to confine a plasma without permitting the buildup of cooperative phenomena which would carry particles very rapidly to the walls of the discharge chamber.
Streak camera	A camera which, by means of an internal rotating mirror, sweeps the image over a strip of film, thereby providing a continuous record of the behavior of the subject over a brief period of time.
Temperature	A measure of the energy of random motion of an assembly of particles (e.g., in a gas).
Thermonuclear conditions	The achievement of an adequately confined plasma having temperature and density sufficiently high to yield significant release of energy from fusion reactions.
Torus or toroid	As used here, a doughnut-shaped tube.
Tritium atom	An isotope of the hydrogen atom with one proton and two neutrons in its nucleus, and a single orbital electron.
Triton	The nucleus of the tritium atom.
Z-value	See atomic number.

APPENDIX VI

GLOSSARY OF SYMBOLS

A	Mass number; equal to the number of nucleons in a nucleus.
B	Magnetic field strength (B_Z refers to an axial magnetic field, B_θ to an azimuthal field).
β	Ratio of plasma pressure to magnetic pressure outside plasma [$= nkT/(B^2/8\pi)$].
c	Velocity of light.
D	Deuteron.
d	Diffusion rate.
e	Electronic charge.
ev	Electron volt.
E_0	Energy released in a fusion process.
F.P.	Fission product.
H	Hydrogen.
k	Boltzmann's constant ($= 1.38 \times 10^{-16}$ erg/°K).
°K	Degrees Kelvin.
kev	Kilo electron volt (= 1000 ev).
λ	Mean free path.
m	Electron mass.
M	Mass of a nucleon; $M_{\rm p}$ and $M_{\rm n}$ refer to the mass of the proton and neutron, respectively.
Mev	Million electron volts (= 1,000,000 ev).
n	Neutron.
n	Density.
N	The number of neutrons in a nucleus.
p	Proton.
P_B	Pressure which can be exerted by a magnetic field ($= B^2/8\pi$).
P_g	Power generated within a plasma ($= \frac{1}{2}n^2\overline{\sigma v}E_0$).
P_p	Pressure exerted by a plasma ($= nkT$).
P_r	Power radiated away from a plasma by bremsstrahlung ($= 1.42 \times 10^{-27}Z^2n_in_eT^{1/2}$).
σ	Cross section.
T	Triton.
τ	Confinement time.
v	Velocity.
Z	Atomic number; equal to the number of protons in a nucleus.
r	Radius of discharge tube.
R	Radius of curvature.

APPENDIX VII

PARTICIPATION IN SHERWOOD CONFERENCES*

U. S. Authors and Conferences at which Papers were Given

Key:
1. Denver 1952
2. Berkeley 1953
3. Princeton 1954
4. Livermore 1955
5. Princeton 1955
6. Gatlingburg 1956
7. Berkeley 1957
8. Washington 1958

Argonne National Laboratory

Gruen, D. N.	8	Kierstead, H. A.	8

Brookhaven National Laboratory

Snyder, H.	4 6

Cambridge Air Force Research Center

Levine, M. A.	5	O'Day, M.	5

Cornell University

Smith, L. P.	2 3 4

General Electric Company

Tonks, L.	4

Los Alamos Scientific Laboratory

Baggett, L. M.	4 5	Elmore, W. C.	8
Boyer, K.	7 8	Ferrell, R.	4
Briscoe, W. L.	4	Hagerman, D. C.	5 6 7
Brousseau, A. T.	6	Hammel, J. E.	8
Brueckner, K. A.	5	Holladay, J. C.	3 4
Bullis, W. M.	7	Honsaker, J.	8
Burkhardt, L. C.	3 4 5 6 7 8	Josephson, V.	5 7
Dreicer, H.	4 5 6 8	Karr, H. J.	5 7 8
Dunaway, R.	4 5 6	Little, E. M.	6 8

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* The last two conferences also included speakers from the United Kingdom

Los Alamos Scientific Laboratory (cont'd)

Livermore, G.	7	Schofield, A. E.	6 7
Longmire, C. L.	3 4 5 6 7 8	Scott, F. R.	4 6 7
Lovberg, R. H.	5 6 7 8	Stovall, E. J., Jr.	3
Marshall, J., Jr.	8	Stratton, T. F.	3 4 6 7 8
Mather, J. W.	5 6 7	Suydam, B. R.	8
Morgan, M.	4	Trigger, K. R.	6
Nagle, D. E.	7 8	Tuck, J. L.	1 2 3 4 5 6 7 8
Osher, J.	8	Van Duren, A.	4 5
Phillips, J. A.	3 4 5 7 8	Wagner, J. J.	6
Quinn, W. E.	8	Watson, K. M.	5 6 7 8
Ribe, F. L.	7 8	Whitmer, R. F.	5
Riesenfeld, W. G.	8	Wieneke, J. R.	3
Rosenbluth, M. N.	4 5 6	Williams, A. H.	4 7
Sawyer, G. A.	3 4 6 7 8	Wyld, H. W., Jr.	6

Massachusetts Institute of Technology

Allis, W. P.	1 6	Brown, S. C.	7 8

Naval Research Laboratory

Aitken, A. H.	7	Kolb, A. C.	6 7 8
Bennett, W. H.	4	Theus, R. B.	6 7
Harris, E. G.	6 7 8		

New York University

Berkowitz, J.	5 6 7	Lomont, J. S.	5
Friedrichs, K. O.	3	Morawetz, C. S.	7 8
Gardner, C. G.	7	Morikawa, G. K.	8
Goertzel, H.	6	Rose, M. H.	4 5 6
Grad, H.	3 4 5 6 7 8	Rubin, H.	5 7
Killeen, J.	7 8	Liboff, R.	8

Oak Ridge National Laboratory

Barnett, C. F.	6 7 8	McNally, J. R., Jr.	5 6 7
Bartels, R. C. F.	4 5 6	Neidigh, R. V.	5 6 7 8
Bell, P. R.	8	Normand, C. E.	4 6 7
Blue, C. W.	5 7	Rankin, F. M.	4 5
Downing, A. C.	4	Ruark, A. E.	4 6
Gauster, W. F.	7 8	Shipley, E. D.	3 6 7 8
Goldman, D. T.	8	Simon, A.	3 4 5 6 7 8
Hoy, H. C.	8	Skidmore, M. R.	6 7
Ivash, E. V.	8	Stier, P. M.	6
Luce, J. S.	4 5 6 7 8	Weinberg, A. M.	6
Mackin, R. J., Jr.	7 8	Yonts, O. C.	4 7 8

Princeton University

Backus, G.	8	Kruskal, M. D.	4 5 6 7 8
Bennett, F.	8	Kulsrud, R. M.	5 6 7 8
Bernstein, I. B.	4 5 6 7 8	Lenard, A.	8
Brault, J. W.	5	Mather, N. W.	4
Chen, F. F.	4 5 6	Meservey, E. B.	5 6 7 8
Coor, T.	4 5 7	Mills, R. G.	3 4 5 7
Cunningham, S. P.	4 5 6	Motley, R. W.	8
Dawson, J.	7 8	Oberman, C.	8
Ellis, R. A., Jr.	7 8	Palladino, R. W.	7
Frieman, E. A.	3 4 5 6 7	Rizzo, J. E.	8
Goldman, L. M.	2 4 5 6	Scag, D. T.	6
Gorman, J.	8	Schultz, M. A.	3
Gottlieb, M. B.	3 4 5	Schwarzschild, M.	1
Greene, J. M.	7 8	Spitzer, L., Jr.	1 2 3 4 5 6 7 8
Grove, D. J.	3 5 6	Stix, T. H.	5 6 7 8
Heald, M. A.	4 5 6 7 8	Tuckfield, R. G.	6 7
Johnson, J.	5	Upham, J.	8
Jones, M. S., Jr.	6 7	Van Allen, J. A.	4
Koenig, H.	6	Wakefield, K. E.	5
Kranz, A. Z	7 8	Willis, C. H.	2

Ramo-Wooldridge Corp.

Fried, B. D.	8	Josephson, V.	8

Tufts College

Bostick, W. H.	1 2	Levine, M. A.	5

University of Chicago

Chandrasekhar, S.	8	Goldberger, M. L.	5

University of California Radiation Laboratory

Aplin, C. M.	6 7 8	Colgate, S. A.	3 4 5 6 7 8
Anderson, O. A.	5 6 7 8	Cook, M. W.	8
Baker, W. R.	5 6 7 8	Cummings, D. B.	4
Bing, G.	5	Cummins, W. F.	8
Bostick, W. H.	4 5 6	Damm, C. C.	7 8
Bratenahl, A.	7 8	Eby, F. S.	7 8
Burnett, C.	8	Edwards, D. A.	4 5 6
Carlson, N. W.	7	Ehlers, K. W.	6 8
Carothers, J.	2	Ellis, R. E.	8
Chambers, E. S.	8	Fasolo, J. W.	7
Christofilos, N. C.	7 8	Ferguson, J. P.	6 7 8
Coensgen, F. H.	3 4 5 7 8	Finkelstein, D.	5 6 7 8

University of California Radiation Laboratory (cont'd)

Ford, F. C.	5 6 7 8	Martin, D. F.	4 6 7
Foster, J.	1 2	McIntosh, V. G.	5
Fundingsland, O.	5	McMillan, E.	2
Furth, H. P.	7 8	Mittleman, M. H.	6 7 8
Gardner, A. L.	5 6 7 8	Myers, W. B.	8
Gardner, C. S.	5 8	Newcomb, W. A.	4 5 6 7 8
Garren, A.	5 6 7	Northrop, T. G.	5 6 7
Gibson, G.	6	Parker, N. L.	6 8
Gilbert, F. C.	6	Popp, E. C.	7
Good, M. L.	2	Post, R. F.	1 2 3 4 5 6 7 8
Gow, J. D.	8	Pyle, R. V.	5 6 8
Greyber, H. D.	4 6	Riddell, R. J., Jr.	4 5 6 7
Hall, L. S.	4 5 7 8	Roberts, J. E.	8
Hartwig, E. C.	4 5	Ruby, L.	4 5 8
Henrich, L. R.	5 6 7	Ruedger, D.	4
Hester, R. E.	8	Sherman, A. E.	5
Hill, M. M.	4 6 7	Showalter, D. E.	5
Hiskes, J. R.	4	Smith, L.	7 8
Howard, J. C.	4 5	Spoerlein, R. L.	7
Huber, E. L.	4	Stone, J. M.	7 8
Ise, J., Jr.	5 6 8	Taylor, C. E.	8
Johnson, M. H.	2	Teller, E.	2 3 4 6 7
Judd, D. L.	4 5	Vandermark, H. H.	7 8
Kaufman, A. N.	6 7 8	Voelker, F.	8
Kilpatrick, W. D.	7	Wells, W. M.	8
Kunkel, W. B.	8	Wharton, C. B.	4 5 6 8
Lamb, W. A. S.	5 8	White, R. S.	6
Lasher, D. R.	5	Wilcox, J. M.	8
Lauer, E. J.	5 6 8	Wright, R. E.	7 8
Linlor, W. I.	5 7	York, H.	1 7
MacDonald, W.	4 5	Zizzo, S.	4 5 6 7 8

University of Michigan

LaPorte, O.	2

University of Tennessee

Harrold, E. G., Jr.	8

APPENDIX VIII

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Inquiries concerning the purchase of the AEC reports listed below should be addressed to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C. These may be examined at AEC depository libraries both in the U. S. and other countries.

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APPENDIX IX

PERSONS ASSOCIATED WITH THE SHERWOOD PROJECT

The following list comprises only those whose names are mentioned in this book.

Key

AEC	U. S. Atomic Energy Commission, Washington, D. C.
ANL	Argonne National Laboratory
BNL	Brookhaven National Laboratory
BY	Brigham Young University
C	Carnegie Institute of Technology
Chi	University of Chicago
CIT	California Institute of Technology
CAFRC	Cambridge Air Force Research Center
CU	Cornell University
GD	General Dynamics Corporation
GE	General Electric Company
LASL	Los Alamos Scientific Laboratory
MIT	Massachusetts Institute of Technology
NRL	Naval Research Laboratory
NYU	New York University
ORNL	Oak Ridge National Laboratory
Prin	Princeton University
RW	Ramo-Wooldridge Corporation
S	Stevens Institute of Technology
SRI	Stanford Research Institute
T	Tufts College
UCRL	University of California Radiation Laboratory (/L = Livermore; /B = Berkeley)
U.K.	United Kingdom
UT	University of Tennessee
W	Westinghouse Electric Company

Aitken, A. H. (NRL)
Allis, W. P. (MIT; LASL)
Alpert, D. (W)
Anderson, O. A. (UCRL/B)
Aplin, C. M. (UCRL/L)
Baggett, L. M. (LASL)
Baker, W. R. (UCRL/B)
Barnett, C. F. (ORNL)
Bartels, R. C. F. (ORNL)
Bell, P. R. (ORNL)

Bennett, F. (Prin)
Bennett, W. H. (NRL)
Berger, J. M. (Prin)
Berkowitz, J. (NYU)
Bernstein, I. B. (Prin)
Bernstein, W. (Prin)
Bing, G. (UCRL/L)
Bishop, A. S. (AEC)
Blue, C. W. (ORNL)
Bohm, D. (UCRL; now Australia)
Bostick, W. H. (T; UCRL/L; S)
Boyer, K. (LASL)
Bratenahl, A. (UCRL)
Brault, J. W. (Prin)
Briscoe, W. L. (LASL)
Brobeck, W. (UCRL/B)
Brousseau, A. T. (LASL)
Brower, D. F. (GD)
Brown, G. (MIT)
Brown, S. C. (MIT)
Brueckner, K. A. (LASL)
Bullis, W. M. (LASL)
Burkhardt, L. C. (LASL)
Burnett, C. (Prin)
Burnett, C. R. (UCRL)
Butler, J. W. (ANL)

Carlson, N. W. (UCRL/L)
Carothers, J. (UCRL)
Chambers, E. S. (UCRL
Chandrasekhar, S. (Chi)
Chem, G. F. (LASL)
Chen, F. F. (Prin)
Christofilos, N. C. (BNL; UCRL/L)
Clauser, M. U. (RW)
Cockcroft, J. (U.K.)
Coensgen, F. H. (UCRL/L)
Cohen, F. (Prin)
Coleman, P. (I)
Colgate, S. A. (UCRL/L)
Cook, M. W.
Coor, T. (Prin)
Courant, R. (NYU)
Creutz, E. (C; ORNL; GD)
Cummings, D. B. (UCRL/L)
Cummins, W. F. (UCRL)
Cunningham, S. P. (Prin; GD)

Damm, C. C. (UCRL/L)
Dawson, J. (Prin)
Downing, A. C. (ORNL)
Dreicer, H. (LASL)
Drummond, J. E. (SRI)
Dunaway, R. (LASL; GD)
Dunaway, R. E. (GD)

Eby, F. S. (UCRL/L)
Edwards, D. A. (UCRL/L)
Ehlers, K. W. (UCRL)
Ellis, R. A., Jr. (Prin)
Ellis, R. E. (UCRL)
Elmore, W. C. (LASL)

Fasolo, J. W. (ORNL; UCRL/L)
Faust, W. (NRL)
Ferguson, J. P. (UCRL/L)
Ferrell, R. (LASL)
Finkelstein, D. (NYU: UCRL/L; S)
Fite, W. L. (GD)
Ford, F. C. (UCRL/L)
Foster, J. (UCRL)
Fowler, W. A. (CIT)
Friedrichs, K. O. (NYU)
Frieman, E. A. (Prin)
Fundingsland, O. (UCRL/L)
Furth, H. P. (UCRL/L)

Gardner, A. L. (UCRL/L)
Gardner, C. G. (NYU)
Gardner, C. S. (UCRL/L)
Garren, A. A. (UCRL)
Gauster, W. F. (ORNL)

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Geller, L. (Vitro Engineering Co.)
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Gilbert, F. C. (UCRL/B)
Goertzel, H. (NYU)
Goldberger, M. L. (Chi; LASL)
Goldman, D. T.
Goldman, L. M. (Prin)
Gottlieb, M. (Prin)
Good, M. L. (UCRL)
Gorman, J. (Prin)
Gottlieb, M. B. (Prin)
Gow, J. D. (UCRL/B)
Grad, H. (NYU)
Greene, J. M. (Prin)
Greyber, H. D. (UCRL/L; GE)
Grove, D. J. (W; Prin)
Gruen, D. N. (ANL)

Hagerman, D. C. (LASL)
Hales, R. (BY)
Hall, L. S. (UCRL/L)
Hammel, J. E. (LASL)
Harris, E. G. (NRL)
Harrold, E. G., Jr. (UT)
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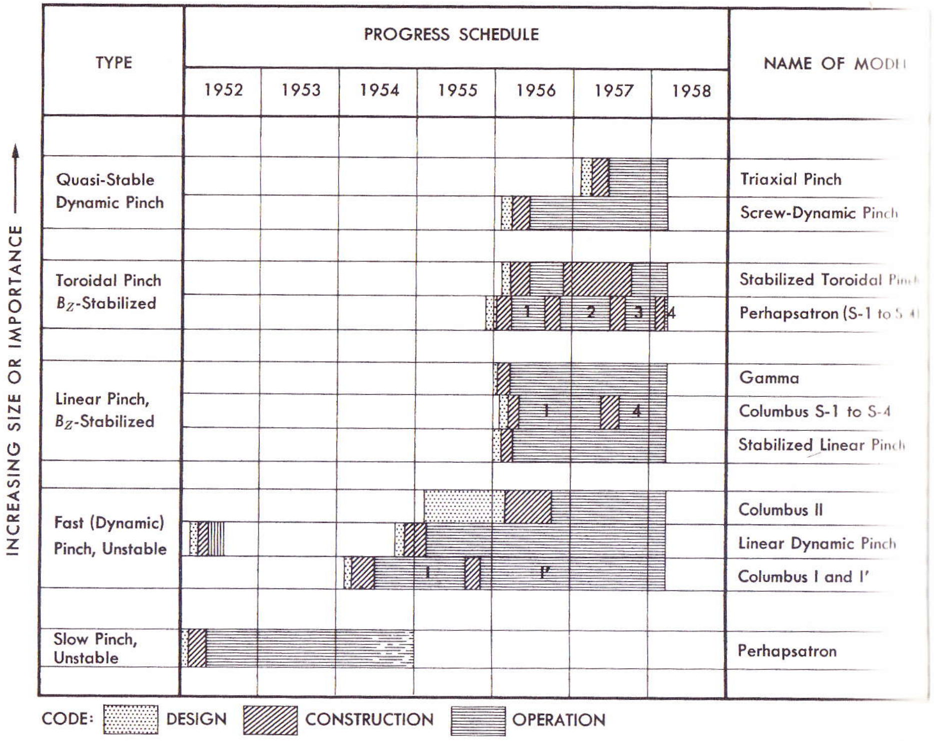
APPENDIX X

CHARTS GIVING DATA ON REPRESENTATIVE MODELS OF THE PINCH, STELLARATOR, AND MAGNETIC MIRROR PROGRAMS

REPRESENTATIVE EXPERIMENTAL MODELS INCORPORATING PINCH-TYPE CONFINEMENT

(Many others are omitted)

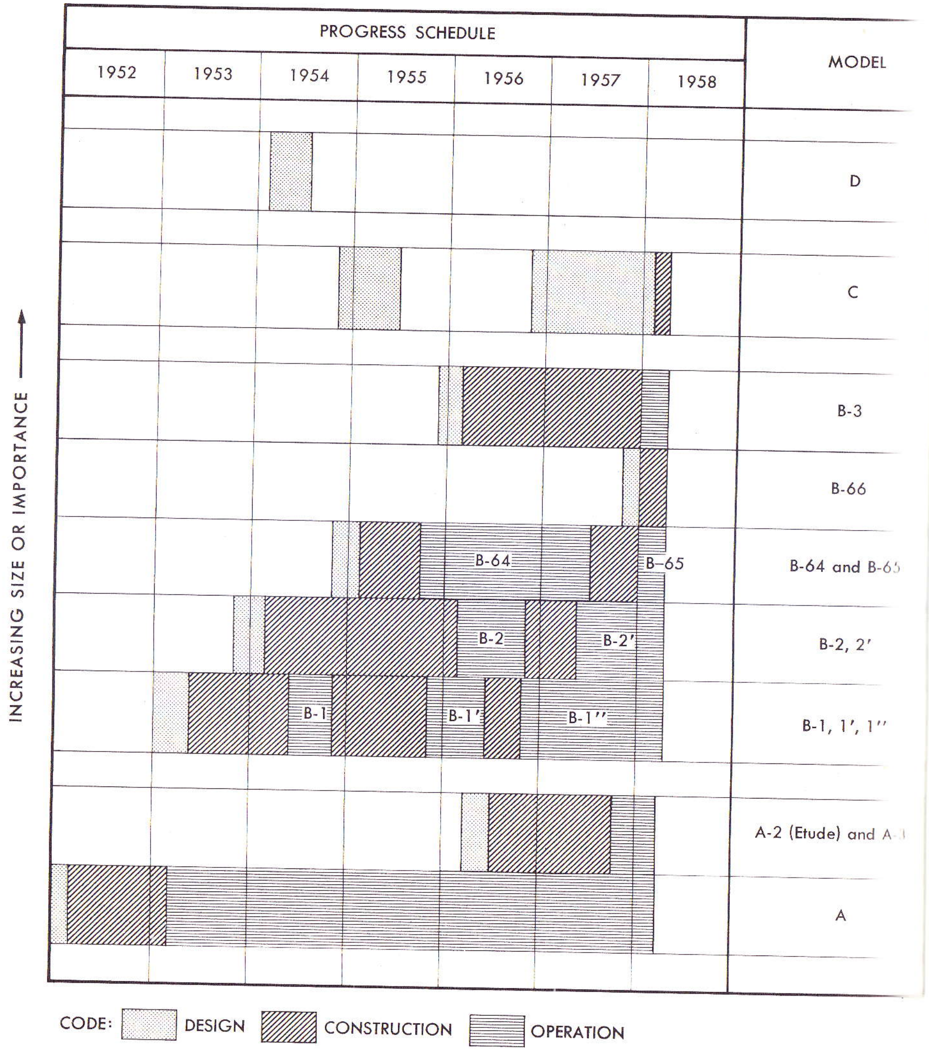


REPRESENTATIVE EXPERIMENTAL MODELS INCORPORATING PINCH-TYPE CONFINEMENT (continued)

Values shown below are for the latest operating version, as of early 1958.

TYPE	NAME OF MODEL	SITE	Tube Bore, cm	Axial Length, cm	Voltage Gradient, volts/cm	Total Power Input, joules/sec	Peak Pinch Current, amp	Estimated Ion Temp., °K	Neutrons per Pulse
Quasi-Stable Dynamic Pinch	Triaxial Pinch	UCRL, Berkeley	10	50	200	5×10^4	2×10^6		10^5
	Screw-Dynamic Pinch	UCRL, Livermore	10	20	2500	10^4	2×10^5		10^5
Toroidal Pinch B_Z-Stabilized	Stabilized Toroidal Pinch	UCRL, Livermore	10	60	100	10^5	4×10^5		10^5
	Perhapsatron (S-1 to S-4)	Los Alamos	14	70	200	9×10^4	4×10^5	6×10^6	10^7
Linear Pinch, B_Z-Stabilized	Gamma	UCRL, Livermore	8	45	200	2×10^4	2×10^5	5×10^5	
	Columbus S-1 to S-4	Los Alamos	13	62	150	10^4	3×10^5	5×10^6	3×10^7
	Stabilized Linear Pinch	UCRL, Berkeley	8	50	500	10^4	2×10^5		
Fast (Dynamic) Pinch, Unstable	Columbus II	Los Alamos	10	30	2000	10^5	2×10^6		3×10^8
	Linear Dynamic Pinch	UCRL, Berkeley	10	100	10,000	2×10^4	2×10^5		10^9
	Columbus I and I'	Los Alamos	7	30	1000	5×10^3	10^5		10^7
Slow Pinch, Unstable	Perhapsatron	Los Alamos	7	70	150	1.6×10^4	5×10^4		

EXPERIMENTAL MODELS INCORPORATING STELLARATOR-TYPE CONFINEMENT



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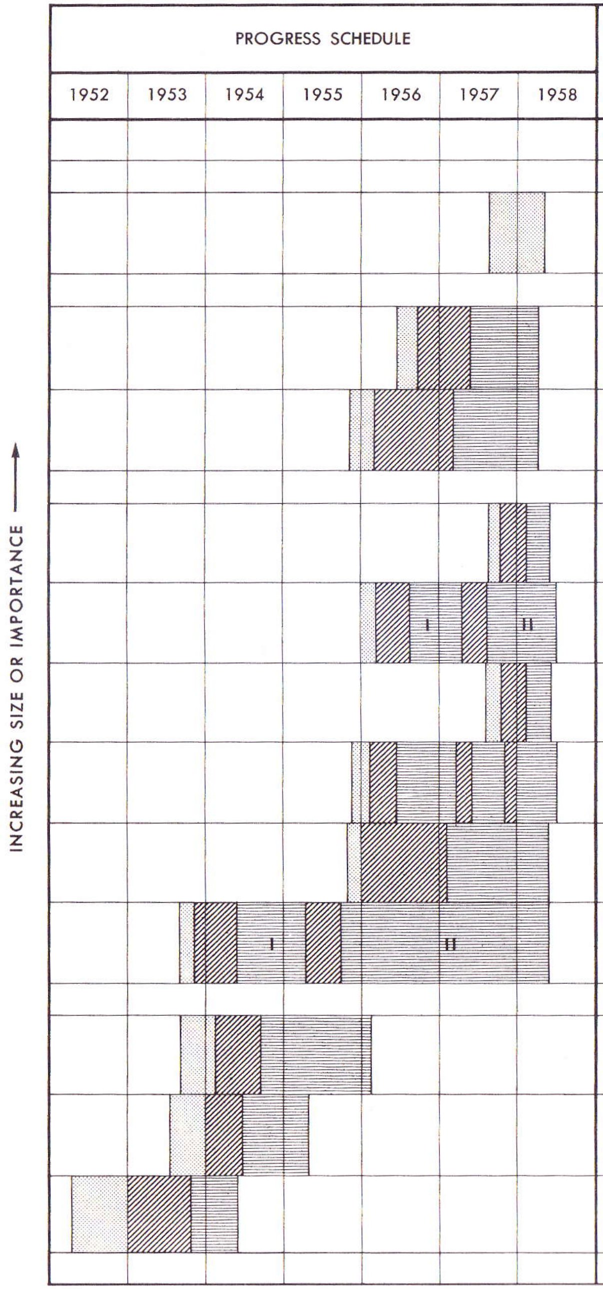
EXPERIMENTAL MODELS INCORPORATING STELLARATOR-TYPE CONFINEMENT (continued)

BRIEF DESCRIPTION	Length, feet	Tube Diam., inches	Method of Heating	Expected ion Temp., °K
Full-scale model for power production; operation on a continuous (rather than pulsed) basis		36	R.F.; DC Pulse and Mag. Pump.	2×10^8
Large experimental model to obtain larger containment of energetic ions and to test effective use of many components of full-scale model	25	8	R.F.; DC Pulse and Mag. Pump.	2×10^8
Improved version of B-2, incorporating a bakable vacuum system, divertor, and stabilizing windings	10	2	R.F.; DC Pulse and ion. cyc.	
Bakable vacuum system inside B-65 type coils. Used for ion-cyclotron resonance heating	10	5	R.F.; DC Pulse and ion. cyc.	10^7
Models built of standard components and incorporating a divertor	6	4	R.F.; DC Pulse	5×10^5
Experimental model to test magnetic pumping	10	2	R.F.; DC Pulse and Mag. Pump.	3×10^6
Experimental model to test ohmic heating. B-1′ incorporates improved magnetic field coils	7	2	R.F.; DC Pulse	7×10^5
Model with steady confining field, quasi-continuous pulsing; helical windings in A-3	4	2		
Preliminary model to test effectiveness of figure-8 configuration and of radiofrequency voltage for initial ionization	6	2	R.F.	~0

EXPERIMENTAL MODELS INCORPORATING MAGNETIC MIRROR CONFINEMENT

EXPERIMENTAL MODELS INCORPORATING MAGNETIC MIRROR CONFINEMENT (Continued)



CODE: ░ DESIGN ▨ CONSTRUCTION ▤ OPERATION

NAME OF MODEL	SITE	BRIEF DESCRIPTION	Over-all Length, feet	Discharge Tube Diam., inches	Peak Central Field, kilogauss	Energy Input, joules	Estimated Ion Temp., °K	Neutrons Per Discharge
			Figures shown below are for latest operating version as of early 1958.					
Orion	Oak Ridge	Intermediate-size model using high-energy molecular ion injection and breakup						
DCX	Oak Ridge	Model to test injection and breakup of high-energy molecular ion beam (600 kev)	3	17	10			
Felix	UCRL Livermore	Model with injection of moderate energy ions (5 to 10 kev) and subsequent compression	9	20		10^6		
Ixion	Los Alamos	Model employing rotating plasmas to test enhanced mirror confinement	3	10	10	5×10^3	2×10^5	10^5
Homopolar I and II	UCRL Berkeley	A model to produce rotating plasmas and test their confinement	0.2	18	20	5×10^4		
Scylla	Los Alamos	Shock-heating and subsequent adiabatic compression			50	3×10^4		$>10^7$
Magnetic Compression Experiment	Naval Research Lab.	Plasma-heating with shock tubes and subsequent adiabatic compression	1	1	500	3×10^5	$>10^6$	$>10^6$
3-Stage Toy Top	UCRL Livermore	An apparatus which provides three successive stages of plasma compression		18 to 3	100		5×10^6	
Table Top I and II	UCRL Livermore	A machine for providing single-stage compression	4	6	50	10^6	$>3 \times 10^6$	
Q-Cumber	UCRL Livermore	A DC machine with low central fields and high mirror ratio to measure particle losses under high-β conditions.						
Toy Top	UCRL Livermore	A small model with very high compression ratios	1	1	200	5×10^4		
Albedo	UCRL Livermore	First mirror machine built; used radiofrequency acceleration to trap particles	10	6	3			

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